1984

CSMP modelling of brushless DC motors.

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

CSMP MODELLING OF
BRUSHLESS DC MOTORS

by

Steven M. Thomas

September 1984

Thesis Advisor: A. Gerba

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
CSMP Modelling of Brushless DC Motors

5. TYPE OF REPORT & PERIOD COVERED
Master's Thesis; September 1984

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Steven M. Thomas

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93943

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Postgraduate School
Monterey, California 93943

12. REPORT DATE
September 1984

13. NUMBER OF PAGES
88

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)
Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Brushless DC Motors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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performance curves as speed, current and power versus torque. Electronic commutation based on Hall effect sensor positional feedback is simulated. Steady state motor behavior is studies under both constant and variable air gap flux conditions. The variable flux takes two different forms. In the first case, the flux is varied as a simple sinusoid. In the second case, the flux is varied as the sum of a sinusoid and one of its harmonics.

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CSMP Modelling of Brushless DC Motors

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1984

ABSTRACT

Recent improvements in rare earth magnets have made it possible to construct strong, lightweight, high horsepower DC motors. This has occasioned a reassessment of electromechanical actuators as alternatives to comparable pneumatic and hydraulic systems for use in flight control actuators for tactical missiles. This thesis develops a low-order mathematical model for the simulation and analysis of brushless DC motor performance. The model is implemented in CSMP language. It is used to predict such motor performance curves as speed, current and power versus torque. Electronic commutation based on Hall effect sensor positional feedback is simulated. Steady state motor behavior is studied under both constant and variable air gap flux conditions. The variable flux takes two different forms. In the first case, the flux is varied as a simple sinusoid. In the second case, the flux is varied as the sum of a sinusoid and one of its harmonics.

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I. INTRODUCTION

Direct current electric motors are gaining wider use in space applications where long life, high reliability, high torque and light weight are critical factors. In recent years, advances in magnet technology and materials, especially the use of rare earth magnets, have made possible significant improvements in the torque to inertia ratios of permanent magnet (PM) motors. Samarium cobalt is one such rare earth magnetic material. The great potential of the rare earth magnets derive from their inherent high flux density and high coercivity properties. Higher flux densities mean greater developed motor torque while high coercivity means greater innate resistance to demagnetization which permits thinner magnet sections. The two factors in combination result in increased mechanical power and energy product with decreased physical size and weight.

Brushless dc motors belong to this class of permanent magnet motors and thus enjoy their improved torque to size characteristics. In fact, brushless dc motors are significantly smaller than either their ac counterparts or conventional brush-type dc motors on an equal horsepower basis. Compared to its conventional counterpart, a brushless dc motor's structure is "inside out." In the brushless configuration, the permanent magnets are attached to the rotor and the conducting coils are placed in the stator. As its name suggests, brushes have been eliminated from this type of motor. Instead, commutation of current in the stationary armature is accomplished electronically by switching on the appropriate windings via transistors specially designed to provide the high currents needed for motor power. In order to sequence the current to the coils, the commutation circuitry is provided rotor position feedback from sensing

devices, most commonly from Hall effect sensors. These are simple semiconductor devices that develop a polarized voltage depending upon the magnetic field passing through them. Small, highly sensitive and reliable, Hall effect sensors require little power to operate and thus are widely used.

Brushless dc motors possess all the advantages traditionally associated with conventional dc motors such as linear torque-speed characteristics, excellent response times and high efficiency. In addition, there are a number of important advantages that brushless dc motors possess over standard brush-type dc motors. An obvious advantage is that electronic commutation means the elimination of commutators, the wear and tear of brushes, and the build up of carbon dust which heretofore significantly limited the life of the standard dc motor. Since electronic current switching essentially involves no component wear, there results improved reliability and enhanced lifespan. As well as being subject to wear and tear, the action of brushes sliding over commutators also generates radio frequency interference (RFI) which is a severe liability in many applications. In fact, it is often in hostile and explosive environments that the advantages of dc motors are most needed. Another benefit is in heat transfer characteristics. By placing windings in the stator the thermal path to the environment is made shorter and more direct. With the removal of heat thus enhanced, mechanical and electrical malfunctions due to heat are reduced. A further important advantage of the brushless dc motor is in the area of motor speed variability. Whereas ac motors usually operate at one speed fixed by the powerline frequency, any dc motor's speed can be changed to meet varying power requirements by simply adjusting the dc input voltage. The electronic commutation scheme of the brushless dc motor lends itself nicely to just

this type of variable speed control. It is a relatively simple matter to attach to the commutation circuit board a small, inexpensive microprocessor whose logic can be programmed to run the motor at any of several speeds or in either direction. A single motor can thus be programmed, in place if desired, so that its speed, direction and torque are matched to a particular application.

There are at least as many applications for brushless dc motors as there are for brush-type motor systems as well as a host of new applications. Of particular relevance to this thesis is the use of brushless dc motors in flight control actuator sytems of Navy tactical missiles, in particular, the cruise missile. There are three general types of actuators that are in use in missile systems: pneumatic, hydraulic and electromechanical. The maneuvering requirements of the more advanced tactical missiles call for high control torques which heretofore could only be produced by high pressure pneumatic or hydraulic actuators. Both of these actuator systems are more susceptible to mechanical malfunction than their electrical counterparts. With the improved torque to inertia ratios resulting from better rare earth magnet materials and the higher mechanical reliability due to removal of brushes, as well as other advantages previously enumerated, the brushless dc motor is in a position to compete with most pneumatic and hydraulic systems. This thesis is but one part of a detailed study of the state of the art in electromechanical actuators as applied to the cruise missile system [Ref. 1].

II. NATURE OF THE PROBLEM

A. PROGRAMMING LANGUAGE

The objective of this thesis is to create a simplified low-order mathematical model that will accurately simulate the response of a brushless dc motor. The IBM Continuous System Modeling Program (CSMP) was chosen for use since it is a user-oriented computer language specifically created for modeling dynamic physical systems and is one of the most widely used in this area [Ref. 2]. It has the flexibility of determining the response of a system that is modeled either in a block diagram format or as a set of ordinary differential equations. While CSMP is an offshoot of IBM's Digital Simulation Language, it embodies Fortran as its source language and retains much of Fortran's capability and flexibility. CSMP is an applications-oriented program intended for use with the IBM mainframe systems. The utility and ease of using this program language stems from simplified program control statements that almost exactly describe the mathematical equations or physical variables of the system and from the flexibility of its program structure which contains preprogrammed function blocks that obviate the need for complicated subroutine programming. In essence, CSMP was chosen because it permits the user to concentrate on the details of the physical system rather than on the time-consuming complexities of programming.

B. SYSTEM BLOCK DIAGRAM

The block diagram format was chosen as the basis for the CSMP program since it is a convenient way of analyzing the input-output relationships of a physical system and the

flow of signals thrcugh it without having to refer to the system equations. The basic idea of a block diagram stems from the application of Laplace transforms to a system's integro-differential cr differential equations. In effect, a differential equatien is rendered into a simpler algebraic expression which, in turn, becomes a fundamental equatien of a system's functional blocks. Each block indicates the relationship between its input driving signal and output response; ie., the transfer function of the input and output. The transfer function is defined as the ratio of the Laplace transform of the output to the transform of the input with all initial conditions assumed to be zerc. A block's transfer function does not include any information about the internal structure of that part of a system, merely the transformation of a signal between two pcints in a system. Furthermcre, it should be borne in mind that all physical systems have certain transfer characteristics that are actually nonlinear to some extent. A dc motor system can be fairly accurately described using the transfer function approach to modeling and, when nonlinear transfer characteristics exist, CSMP modeling can usually be obtained from preprogrammed ncnlinear function routines.

C. DEVELOPMENT OF MCTOR SYSTEM EQUATIONS

In crder to construct the block diagram of a system, one approach is to identify the various mathematical relationships between the components of the system and to write balance equations that will identify each individual block comprising the system. The system equations for a brushless dc motor are presented in chapter three where all the details of the logic control and switching of transistors for ccmmutation of the motor are developed. What follows is a simplified input-output characteristics model of the type

that has been a standard for brush-type dc motors used in control system studies [Ref. 3]. The development of this input-output model is the first learning step in the modeling process for the brushless dc motor and has the additional usefulness of being a tool for a concurrent mechanical engineering study of load torque requirements for the motor [Ref. 1].

To write the electrical balance equation describing a basic dc motor, the classical loop method based on Kirchoff's voltage law is applied to the equivalent motor circuit (Figure 2.1).

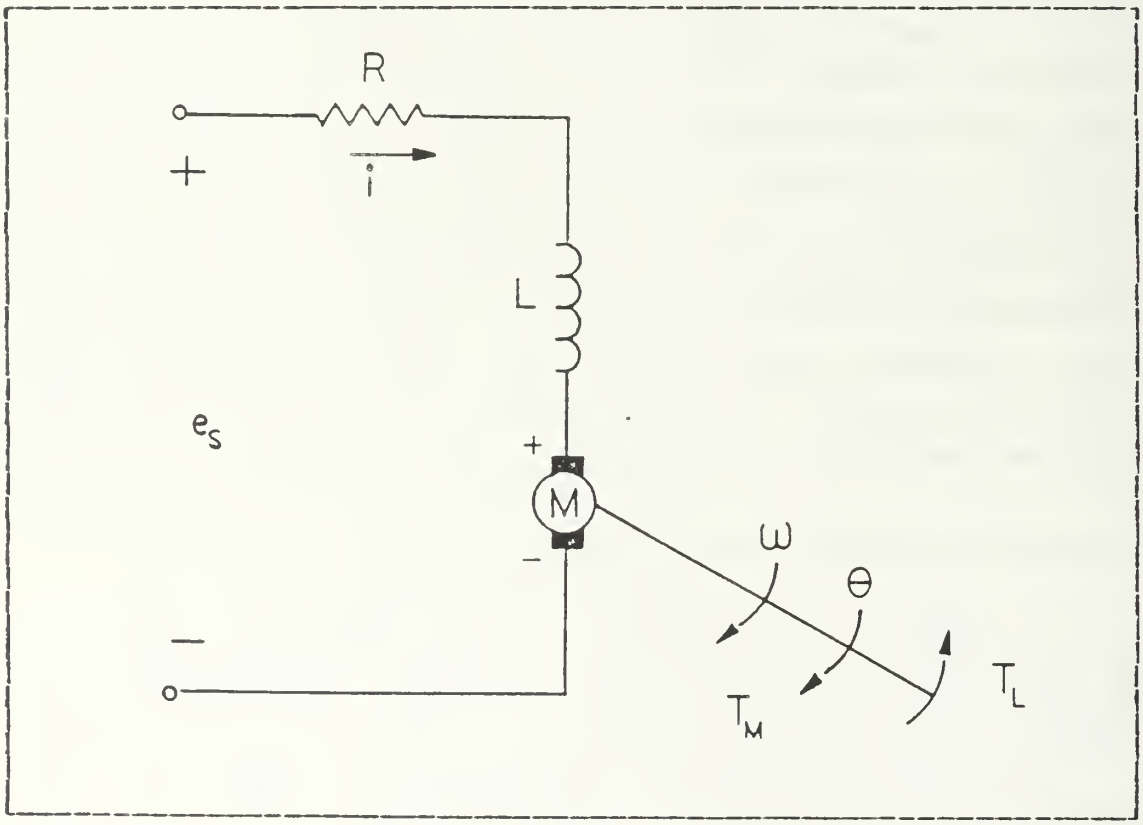

Figure 2.1 Equivalent DC Motor Circuit

The basic dc motor has the coil windings on the armature and the magnetic field source on the stator. In the case of the brushless dc motor, the rotor consists of permanent magnets that produce the magnetic field and the stator contains the coil windings. The Kirchoff Law for the stator circuit is

$$es(t) = Ldi/dt + Ri(t) + eb(t) \qquad \text{(eqn 2.1)}$$

where R and L are the stator resistance and inductance respectively, and eb(t) is the back emf. When a conductor moves in a magnetic field, or there is any relative motion between the magnetic field source and the conductor, a voltage is generated across the terminals of the conductor. In the case of the dc motor, the voltage is proportional to the shaft velocity and tends to oppose the current flow. The relationship between the back emf and the shaft velocity is

$$es(t) = (Km*\phi)*wm(t) = Kb*wm(t) \qquad \text{(eqn 2.2)}$$

$$es(t) = Kb*d\theta m(t)/dt \qquad \text{(eqn 2.3)}$$

Substituting and rearranging equations 2.1 and 2.2 into their differential forms gives the following two equations.

$$di/dt=(1/L)*es(t)-(R/L)*i(t)-(1/L)*Kb*wm(t) \qquad \text{(eqn 2.4)}$$

$$d\theta m(t)/dt = wm(t) \qquad \text{(eqn 2.5)}$$

The basic balance equation that describes the motor as a mechanical system derives from application of Newton's laws of motion to the system components. The dynamic equation for a motor coupled to its load is

$$tm(t) = J*dwm(t)/dt + B*wm(t) + tl(t) \qquad \text{(eqn 2.6)}$$

where tl(t) is the load torque. Rearranging the equation it becomes

$$dwm(t)/dt=(1/J)*tm(t)-(1/J)*tl(t)-(B/J)*wm(t) \quad \text{(eqn 2.7)}$$

B is the total viscous friction coefficient of the motor and is comprised of the sum of the viscous friction due to the motor, Bm, and the load, Bl, as seen by the motor shaft. Likewise, J is the total system inertia comprised of the sum of the motor inertia, Jm, and of the load inertia, Jl, reflected through the coupling device to the motor shaft. Both Bl and Jl are functions of the motor's speed reducing mechanism where N is the speed reduction ratio (N>1). The following equations summarize the foregoing.

$$B = Bm + Bl \quad \text{(eqn 2.8)}$$

$$J = Jm + Jl \quad \text{(eqn 2.9)}$$

$$Bl = Blp/N \quad \text{(eqn 2.10)}$$

$$Jl = Jlp/N \quad \text{(eqn 2.11)}$$

Jlp and Blp are the inertia and viscous friction seen at the load side of the system. Since a dc motor is essentially a torque transducer that converts electrical energy into mechanical energy, the following equation is necessary to show the relationship amoung the developed torque, tm(t), the air gap flux, ϕ, and the stator current, i(t).

$$tm(t) = (Km*\phi)*i(t) \quad \text{(eqn 2.12)}$$

Because the magnetic field in the motor is assumed uniform and constant, this can be simplified to

$$tm(t) = Kt*i(t) \qquad \text{(eqn 2.13)}$$

where Kt is the torque constant of the motor.

Equations 2.1 through 2.13 represent the cause and effect equations of the system. The application of es(t) produces a current flow which causes the torque and the back emf tc be generated. The torque produced then causes the angular displacement $\theta m(t)$. Given the differential equations of the system, the Laplace transform can be applied and the block diagram of the system generated. As an example, the block fcr equation 2.1 is generated as follows

$$es(t) - eb(t) = L*di/dt + R*i(t) \qquad \text{(eqn 2.14)}$$

$$\mathcal{L}\{es(t) - eb(t)\} = \mathcal{L}\{L*di/dt + R*i(t)\} \qquad \text{(eqn 2.15)}$$

$$En(s) = Es(s) - Eb(s) = (Ls + R)*I(s) \qquad \text{(eqn 2.16)}$$

$$I(s)/En(s) = Is/(Es - Eb) = 1/(Ls + R) \qquad \text{(eqn 2.17)}$$

Performing the same operation to the remaining differential equations, the block diagram in Figure 2.2 results.

It is important to note that while a dc motor is basically an open-loop system, the back emf of this type of dc motor acts as a natural feedback loop that tends to improve the stability of the motor.

Once the basic block diagram is developed, writing a CSMP program is simple and fairly straightforward. Care must be taken, however, to put the block transfer functions into the proper format for CSMP's functional blocks. A copy of the CSMP program for a basic dc motor is provided in Appendix A.

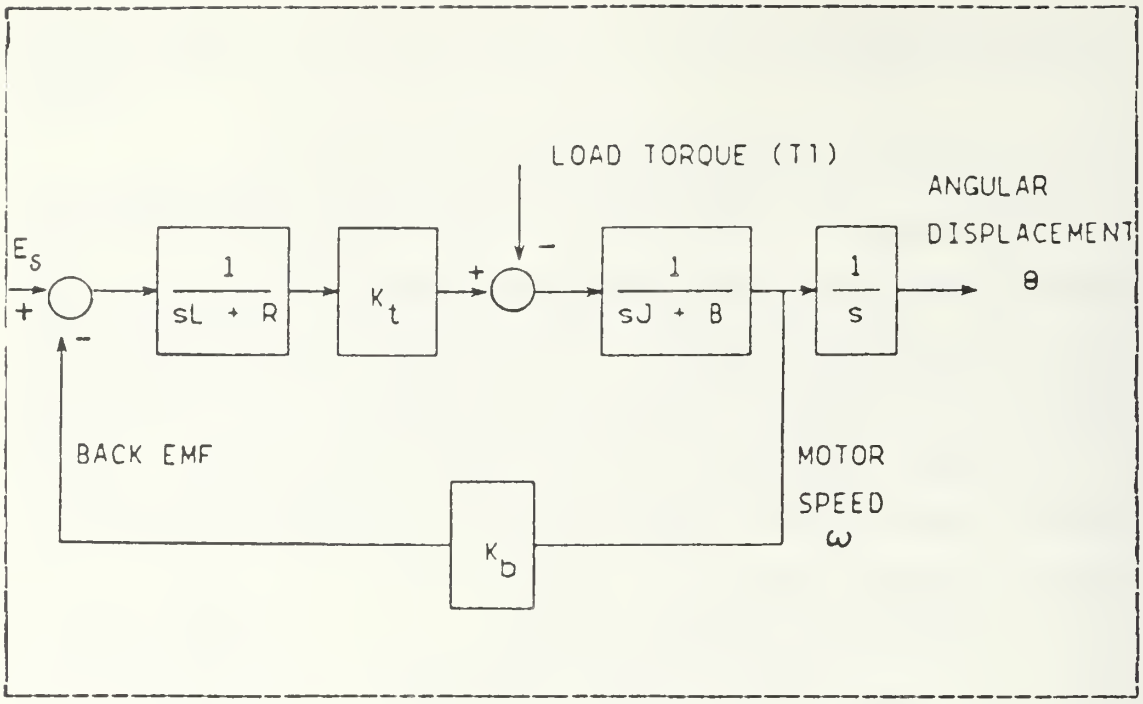

Figure 2.2 Block Diagram of DC Motor

III. CURVE PREDICTION

A. OVERVIEW

One of the purposes of this model is to produce a set of performance curves that accurately simulate a given motor's behavior when operated under varying load conditions. As such the model can be a useful tool for studying the changing performance due to the configuration changes of a motor under development or for observing the behavior of a motor under varying conditions of application or environment. Thus, having developed an input-output computer model for the DC motor, the next step was to assign values to the model parameters and run the program. Program inputs, constants and parameters were assigned values that are typical of brushless DC motors commercially available. Table I provides the parameter values for a given motor that will be used as a generic motor for the following analysis and discussion.

TABLE I

Typical Commercial Motor Parameters

Stator Resistance, R	2.74	ohms
Stator Inductance, L	0.0016	henries
Torque constant, Kt	15.9	oz-in/amp
Back EMF constant, Kb	0.112	volt/rad/s
Rotor Inertia, Jm	0.001	oz-in/s^2
Viscous Friction Coefficient, Bm	unknown	oz-in/rad/s

B. SPEED VS TORQUE CURVE

Specifically, three curves were produced: motor speed vs. generated torque, current vs. torque and output power vs. torque. Since permanent magnet DC motors have linear characteristics, a straight-line curve resulted under all load conditions when the parameters of Table I were inserted into the model and a voltage of 30 VDC was applied. In order to fully understand the individual contributions of the various motor parameters on the speed-torque curve, it was necessary to determine the mathematical relationships between the parameters. Referring to equations 2.1 and 2.5, the electrical and motor equations when considered under steady state conditions become

$$es(t) = R*i(t) + Kb*wm(t) \qquad \text{(eqn 3.1)}$$

$$tm(t) = Kt*i(t) \qquad \text{(eqn 3.2)}$$

Solving for i(t) and combining the equations results in

$$es(t) = (R/Kt)*tm(t) + Kb*wm(t) \qquad \text{(eqn 3.3)}$$

When there is no torque applied to the motor, the current is small enough to neglect and the no-load velocity becomes

$$wnl = es/Kb \qquad \text{(eqn 3.4)}$$

Given that the applied voltage is a constant, it is apparent that knowledge of the value of the back emf constant, Kb, will provide the various no-load speeds for any value of applied voltage. On the other hand, in the absence of any known motor specifications, the no-load speed of a given motor can be empirically measured and then the back emf constant, Kb, can be mathematically derived.

Looking next at the slope of the speed-torque curve, it can be seen that whereas one endpoint of the curve terminates at no-load speed, the other ends at stall which is that value of torque which is large enough to literally stop the motor. From equations 3.1 and 3.2, with wm set to zero the generated torque, tm(t), at stall is ts given by

$$ts = (Kt/R)*es \qquad \text{(eqn 3.5)}$$

Combining equations 3.4 and 3.5, the equation of a straight line for the speed-torque curve results in

$$wm(t) = wnl - (Rm*tm(t)) \qquad \text{(eqn 3.6)}$$

where

$$Rm = R/(Kb*Kt) \qquad \text{(eqn 3.7)}$$

and Rm is the slope factor for the curve, also called the speed regulation constant. Obviously, changing any or all of the parameters will alter the slope factor, Rm. However, the back emf constant, Kb, and the torque constant, Kt, are strictly related by the common factor, air gap flux, ϕ. In fact, when both constants are put in the MKS system of units, Kb in volt/rad/s and Kt in Nm/amp, then they are equal as equation 3.8 shows.

$$Kb(volt/rad/s) = Kt(Nm/amp) \qquad \text{(eqn 3.8)}$$

Thus, knowledge of either constant provides knowledge of the other. Referring to equation 3.7, it can be seen that the final unknowns are the resistance, R, and the slope factor, Rm. If the resistance, R, is known from manufacturer specification sheets, for example, then the slope, Rm, can be

easily solved. On the other hand, if given an empirically measured speed-torque curve, it is now obvious that the curve not only provides Kb which in turn provides Kt, but it also can provide a derived value for motor resistance, R. Once acquired, the three basic parameters, Kb, Kt and R, were plugged into the CSMP model and the speed-torque curve for a 30 VDC input was generated (see Figure 3.1).

This same procedure can be used to produce a family of speed-torque curves if it is desired to study a motor's performance under different input voltages. Figure 3.2 shows the family of curves produced when the values given in Table I were entered into the model.

C. CURRENT VS TORQUE CURVE

With the speed-torque curve understood, the next task was to repeat the same general procedure for the motor current vs. torque. As a starting point, the equation for the steady-state current is given by

$$iss(t) = (es(t) - Kb*wm(t))/R \qquad \text{(eqn 3.9)}$$

Since Kb and R were fixed by the speed-torque curve, generating a current-torque curve was straightforward procedure for any applied voltage (see Figure 3.3).

D. OUTPUT POWER VS TORQUE CURVE

The final performance curve to be studied was the output power vs. torque curve. The basic equation for power is given by

$$P(t) = tm(t)*wm(t) \qquad \text{(eqn 3.10)}$$

$$P(t) = Kt*i(t)*wm(t) \qquad \text{(eqn 3.11)}$$

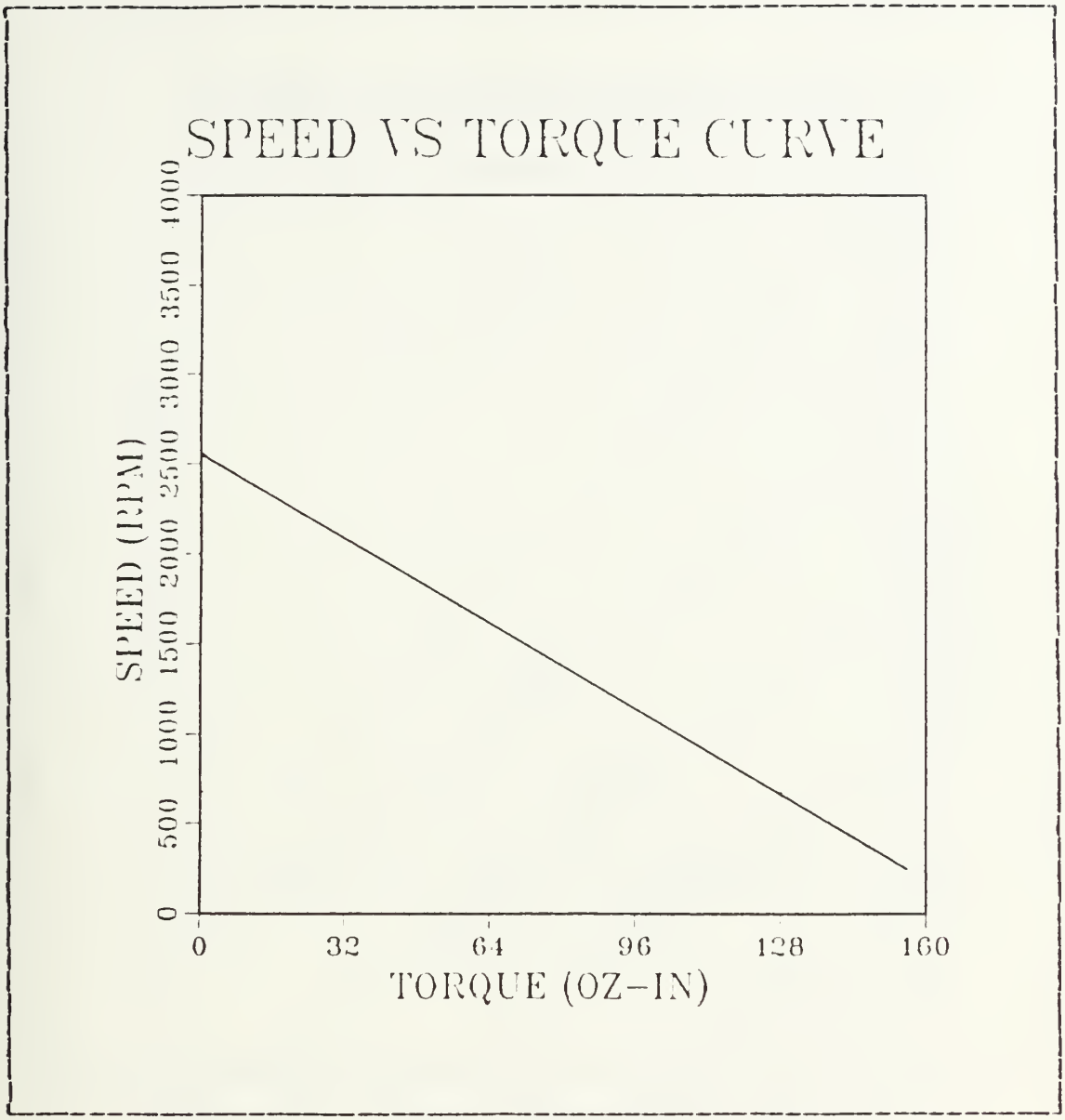

Figure 3.1 Motor Speed vs Torque Curve

where power is measured in watts. Since this equation involves no new constants, producing the power curve was only a matter of adding a line to the existing model which also included a conversion factor for changing the torque units from oz-in/amp to Nm/amp in order for the power to be

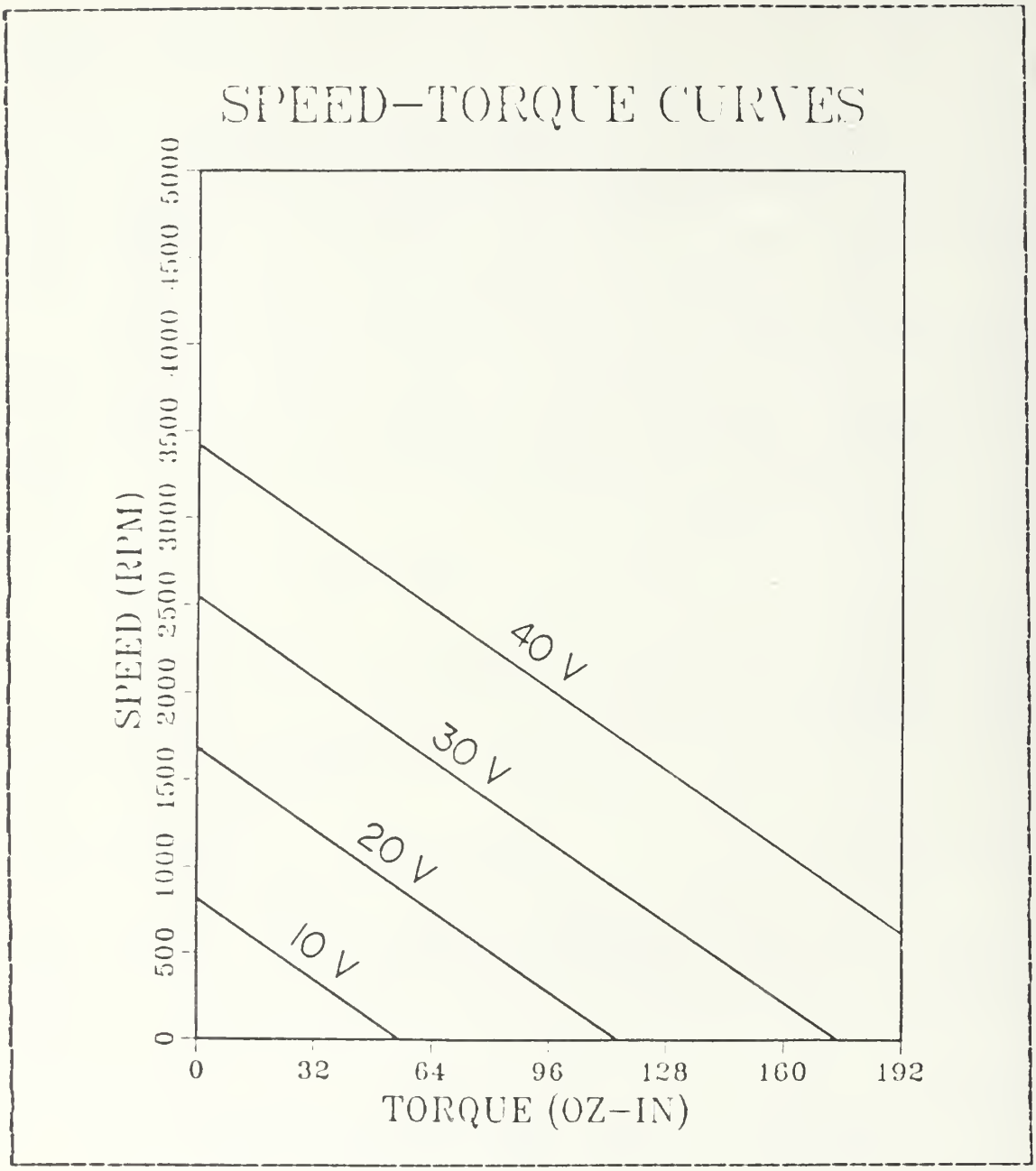

Figure 3.2 Family of Speed-Torque Curves

dimensionally correct in watts. Again running the program with the parameters given in Table I, the model produced the power curve given in Figure 3.4

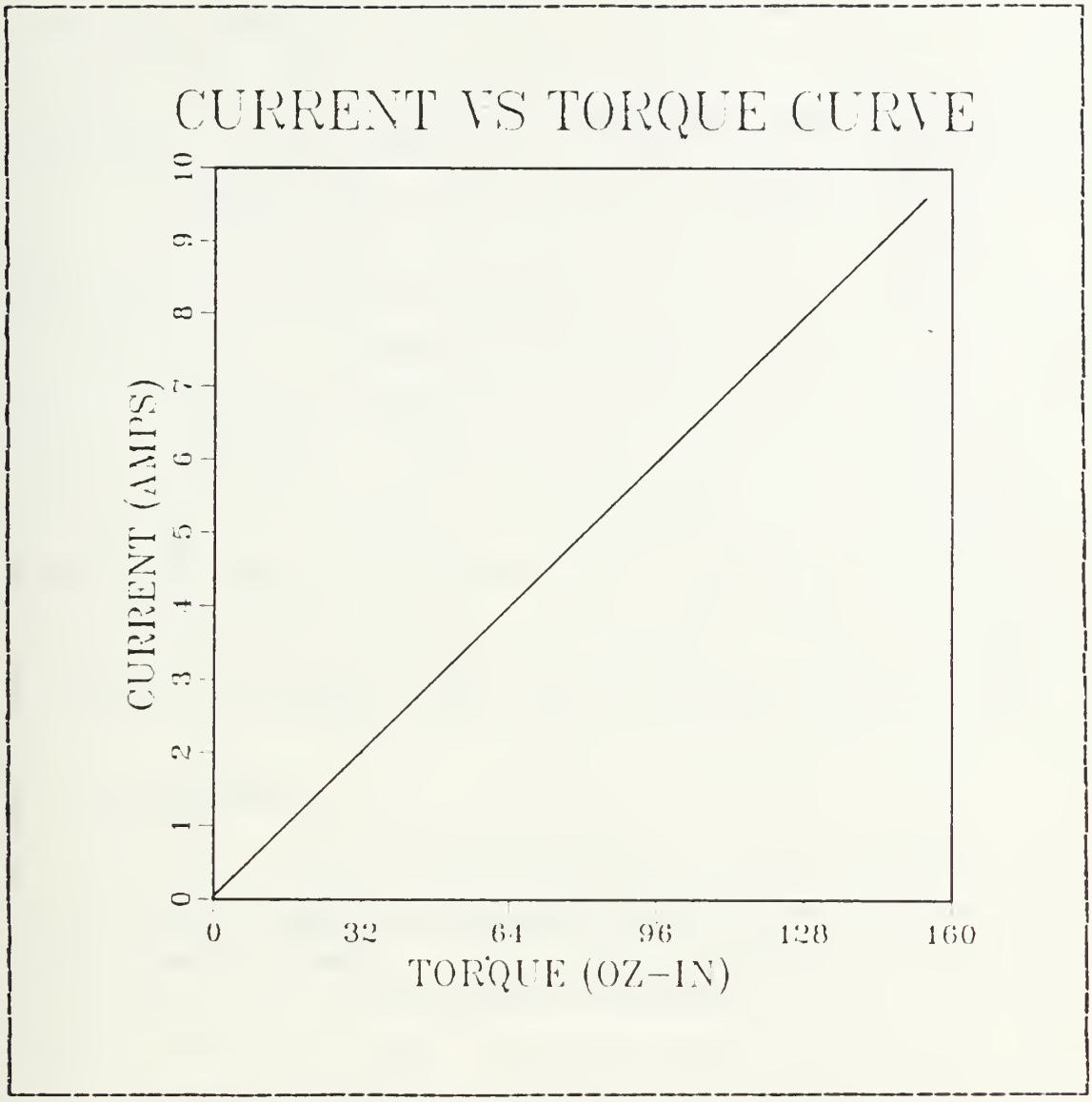

Figure 3.3 Motor Current vs Torque Curve

As expected both the speed-torque and current-torque curves were linear. The power-torque curve is obviously not linear, especially at high loads where the power begins to roll off fairly sharply. From the modelling point of view this is due solely to the fact that the motor slows down faster than the load torque increases (see equation 3.9).

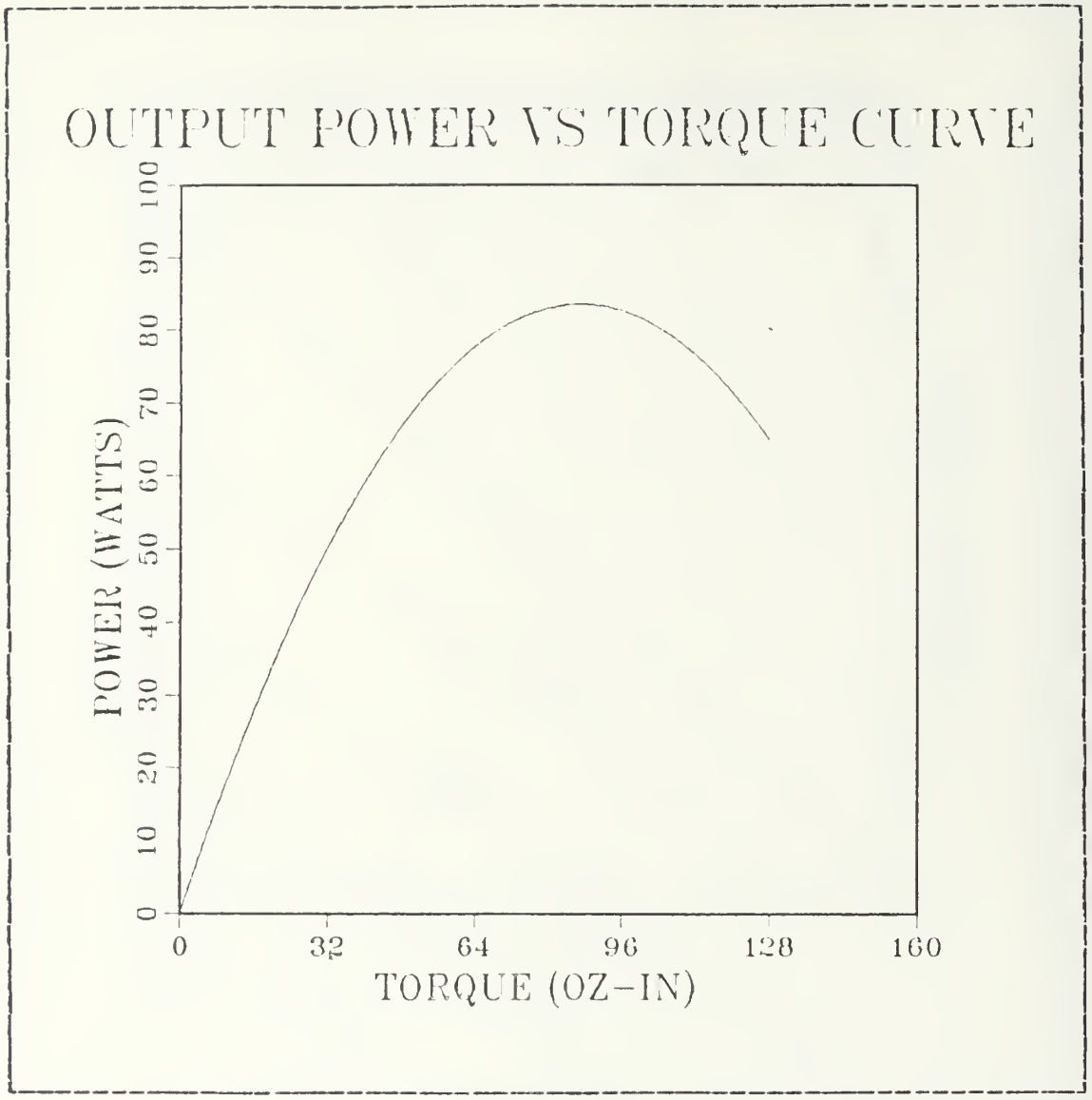

Figure 3.4 Output Power vs Torque Curve

Another factor that further accentuates this power rolloff in an actual motor is the effect due to armature reaction. Whenever a current flows through the motor armature in a permanent magnet dc motor, the armature becomes an electromagnet which produces a flux that tends to oppose the flux produced by the permanent magnets. This has the effect of

partially demagnetizing the permanent magnets. This demagnetization is a reversible effect, meaning that as current returns to zero the permanent magnets return to their full strength. However, as the current increases and armature reaction sets in, it has the effect of decreasing the torque constant, Kt (as well as Kb). As equation 3.9 indicates, this also contributes to the output power rolloff at high loads. Though current permanent magnet DC motors made of rare earth magnets have high coercivity that resists armature reaction, at high levels of rated current a small amount of armature reaction still occurs. For the purposes of this thesis, the model is considered to accurately simulate motor behavior for loads up to the peak power load for the given applied voltage. From that load upward, it is assumed that armature reaction is likely to occur and result in nonlinear behavior which is not included in this model.

E. MOTOR REVERSAL

The final step in the modeling procedure was to reverse the motor's direction and ensure that mirror images of the three curves resulted. To do this, it was first necessary to replace the positive input voltage with a negative counterpart. Next, in order to maintain model consistency where the load torque, tl(t), is treated as a torque that opposes the motion of the motor, it was necessary to modify the model so that the load torque was a positive value. This consisted of creating a CSMP procedure block that identified the input voltage as either positive or negative and then treated the load torque accordingly. Once program bugs were removed, the model accurately simulated motor reversal with proper speed, current and power values for the appropriate load conditions.

IV. ELECTRONIC COMMUTATION

A. SWITCHING ACTION

The next major step in this thesis was to convert the basic model of a standard brush-type dc motor into a three-phase, four-pole brushless dc motor system. Figure 4.1 shows this system with the three-phase stator windings configured in a standard 'star' connection with each winding oriented 120 electrical degrees from the others.

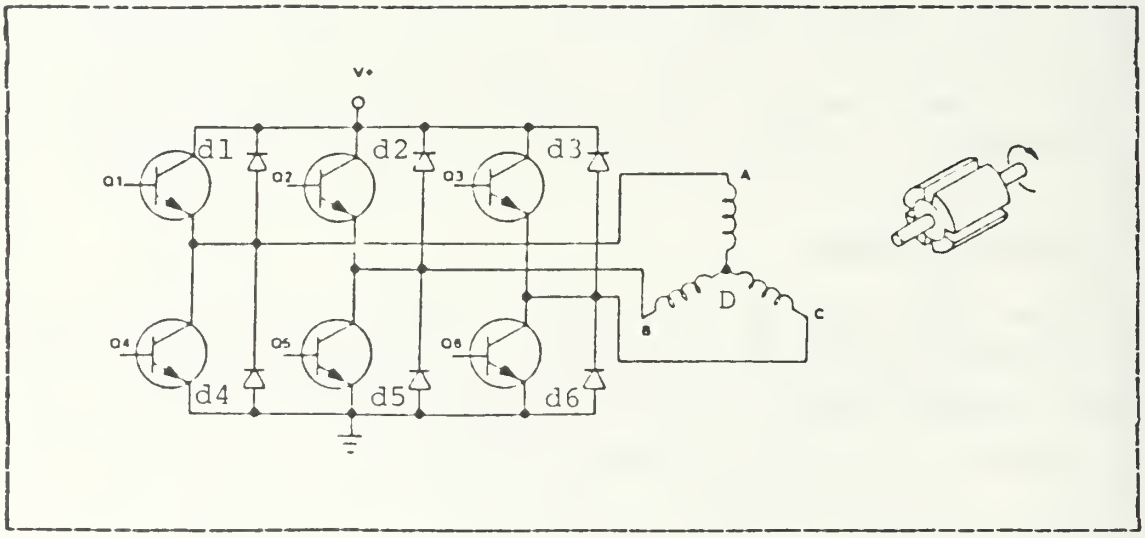

Figure 4.1 Controller Configuration

The six transistors are connected to the ends of each stator leg and through logic-controlled switching action provide three-phase full-wave motor control. Figure 4.2 indicates the switching logic sequence for counterclockwise rotation.

To produce clockwise rotation, the sequence is reversed. In either case, a pair of transistors will be switched at the start of each 30 degree (mechanical) interval which causes current to simultaneously build up in one leg, flow

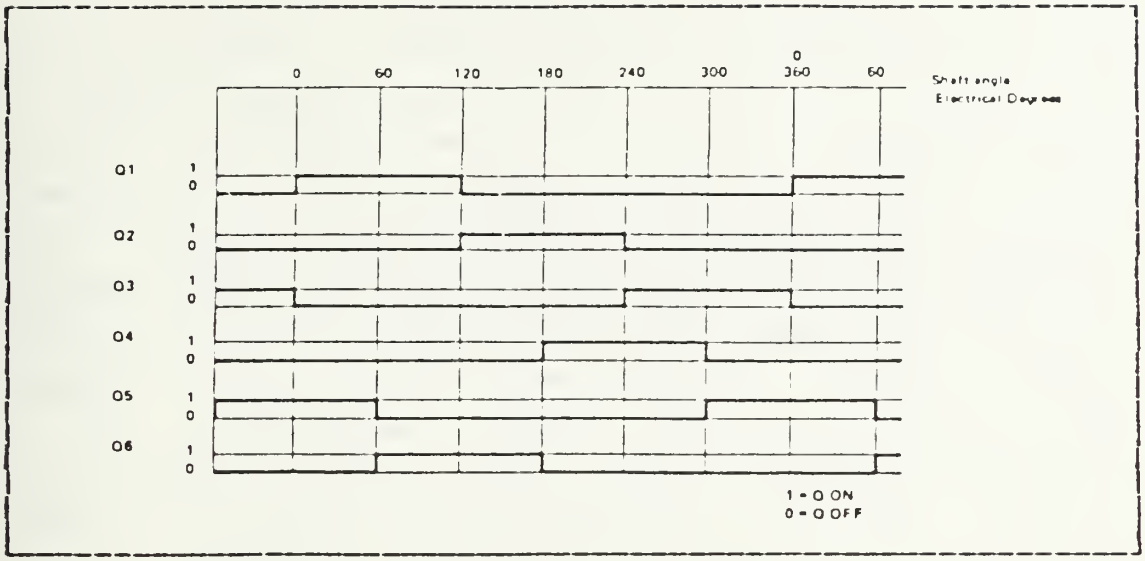

Figure 4.2 Switching Logic of a 3-Phase Brushless DC Motor

steadily in a second, and decay to zero in a third. Given proper sequencing, the net developed torque ideally reaches a steady state value that causes motor rotation at a constant speed in the desired direction.

For windings configured in a star arrangement, it can be seen that conduction is continuous in one leg while commutation occurs in the other two legs. For example, as Q1 and Q5 are energized between 30 and 60 degrees (mechanical), current flows down leg A and into leg B. At the same time, the current through leg C due to the energy storage behavior of an inductor decays to zero through diode, D3 (see Figure 4.1). In the next sequence, 60 to 90 degrees, Q6 is energized and Q5 switched off. Current has reached a steady state flow through leg A, but now it flows down leg C and the current in leg B decays to zero through D2. In the next sequence, 60 to 120 degrees, Q2 is switched on and Q1 switched off. Current has reached steady state flow through leg C but now current builds up and flows from leg B while the current in leg A decays through leg C. This same action

repeats in subsequent commutation states. Looking at point D in Figure 4.1, it can be seen that, since current is always continuous in one leg whether flowing into or from node D, Kirchoff's Current Law requires that the net current flowing in the other two legs must equal the flow in the continuous leg. This permits the following important simplification which was needed later in the modeling process. Namely, the three-legged stator can be approximated by just two windings serially configured. One leg will always accurately reflect steady state flow conditions while the other will be treated as if it were in steady state because the build up in one leg is balanced by decay in the other. It is recognized that this model is a first approximation and that future modeles will require additional refinements in order to adequately represent the effect of switching transients on the transistor and diode elements.

B. HALL EFFECT SENSOR FEEDBACK

As was mentioned in the introduction, the switching action of the commutation circuitry is based upon rotor position feedback from Hall effect sensors. In order to represent electronic switching and postional feedback, as well as the three phase winding configuration, it was necessary to modify the block diagram of Figure 2.1 to that in Figure 4.3

Comparing Figures 2.1 and 4.3, it is seen that the chief difference is in the switching logic block and the addition of two more transfer function blocks to account for the additional windirgs. To better understand the logic relationship between the sensors and the current switches, the truth table for both counterclockwise and clockwise rotation is presented in Table II.

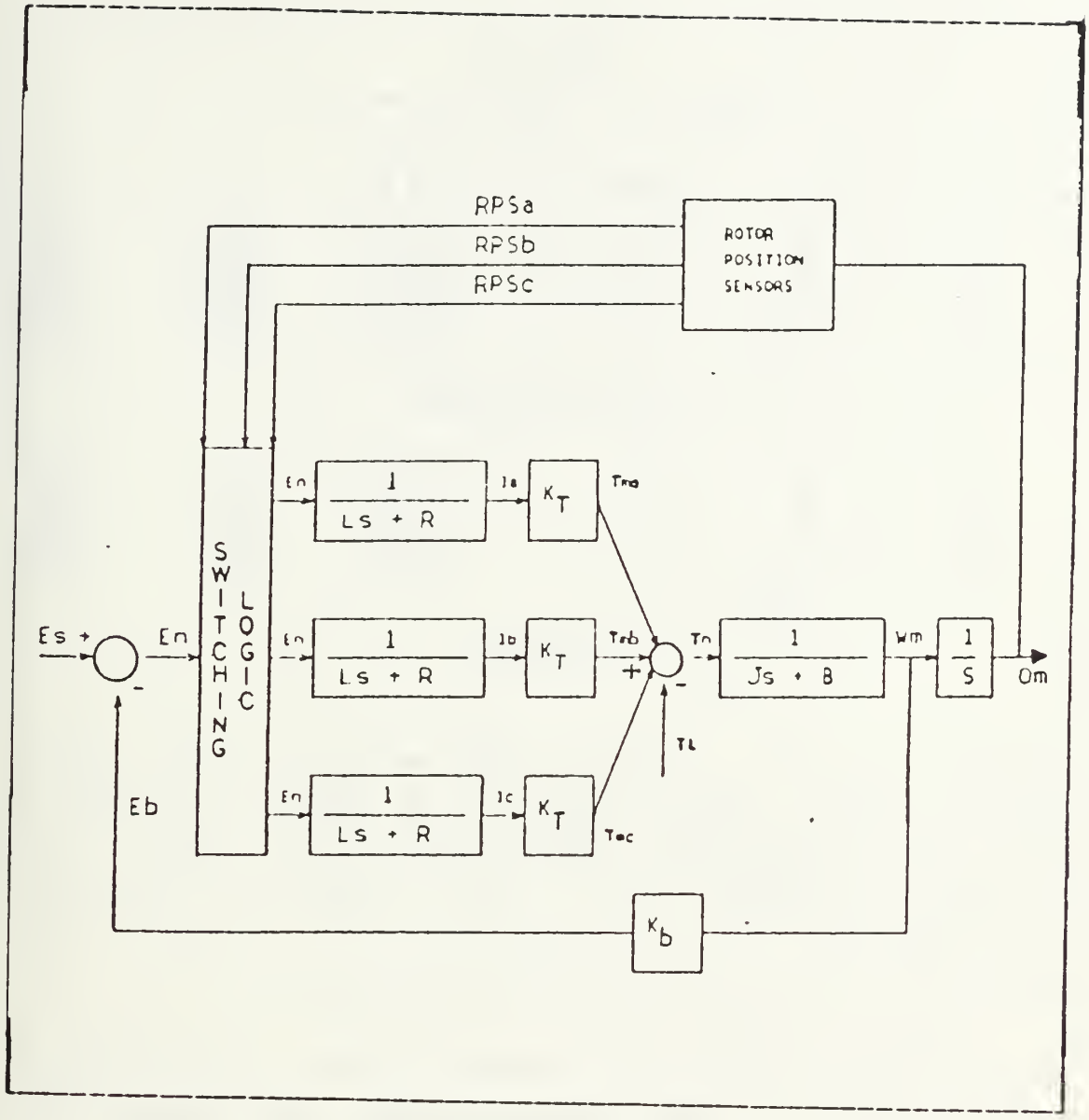

Figure 4.3 Equivalent Circuit With Electronic Commutation.

A brief review of the action af a Hall effect senscr is in order at this point. Consider a conducting material with a constant current flow. When there is no external magnetic field present, the current flows undisturbed in a straight line. But when a magnetic field is applied, a deflecting force, the Lorentz force given by Il x B (where I is the

TABLE II

Sensor and Switching Logic

RPS A	RPS B	RPS C	PH A	PH B	PH C
1	1	0	high	low	open
1	0	0	high	open	low
1	0	1	open	high	low
0	0	1	low	high	open
0	1	1	low	open	high
0	1	0	open	low	high
		COUNTERCLOCKWISE			
0	0	1	low	high	open
1	0	1	open	high	low
1	0	0	high	open	low
1	1	0	high	low	open
0	1	0	open	low	high
0	1	1	low	open	high
		CLOCKWISE			

current, l is the length of the conductor and B is the magnetic field) causes the current to bend and electrons to pile up on one side and positive charges, or holes, to do the same on the other side. Thus a transverse Hall potential difference, Vh, develops across the conductor (see Figure 4.4).

Figure 4.5 shows that in the presence of a sinuscidal magnetic field produced by a rotating magnet, such as one of the pole-pairs of a multiple-pole motor, the induced Hall voltage takes on an ideal square wave shape.

The logic circuitry of the sensor is configured in such a way as to output a logic level 1 for positive Hall voltages and a 0 for negative voltages. Briefly reviewing the action of the motor: as the shaft turns, the rotor position sensors send this information to the switching logic block which then decides which phases are to be made high, low or open in accordance with Table II. Equivalently, the voltage, En, is then applied to the two appropriate windings

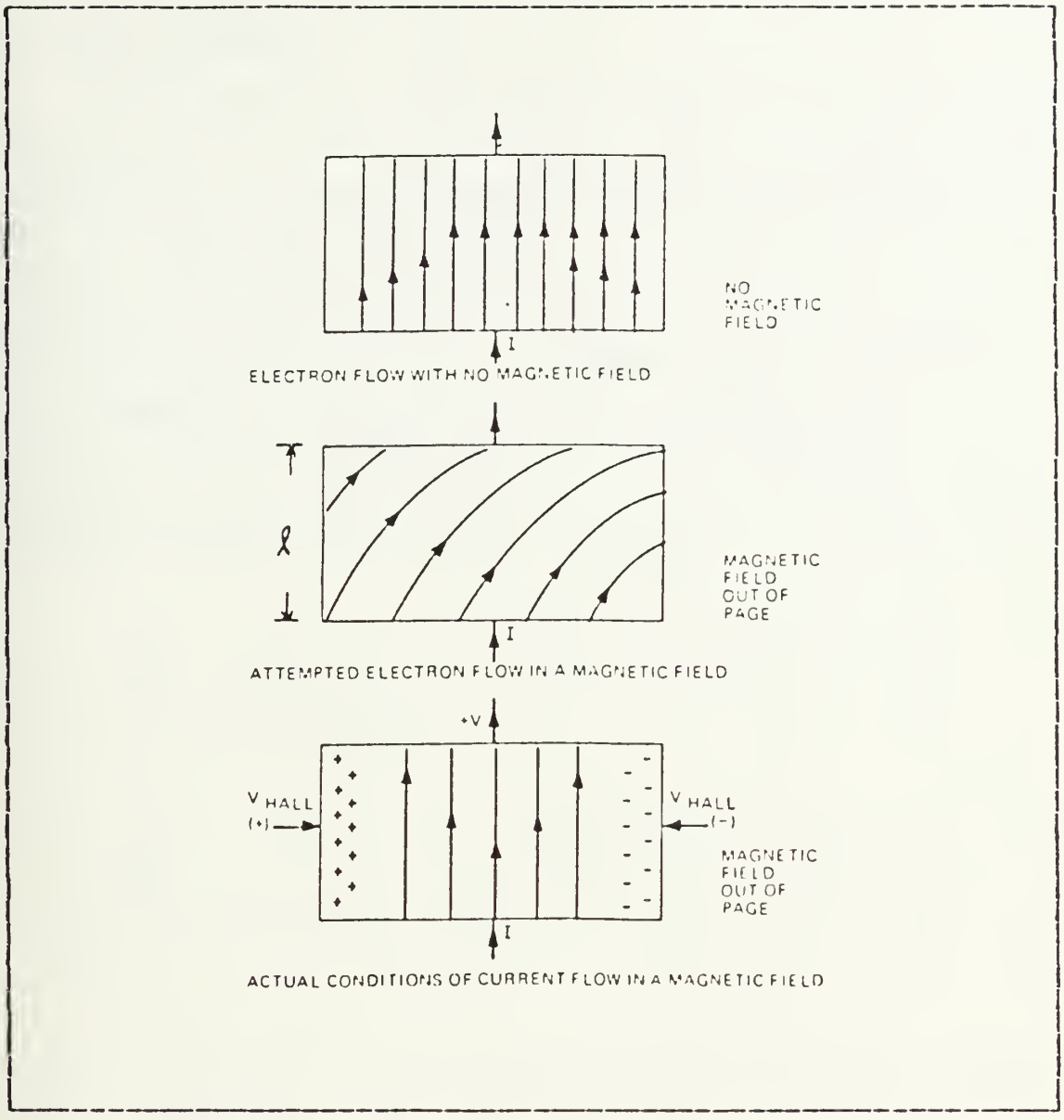

Figure 4.4 The Hall Effect

and zero voltage is applied to the third winding in agreement with the assumption that current is steady in one leg while the commutation in the other two legs is equivalent to a continuous current in one leg. As before, each voltage then produces a current. Because this is assumed to be a

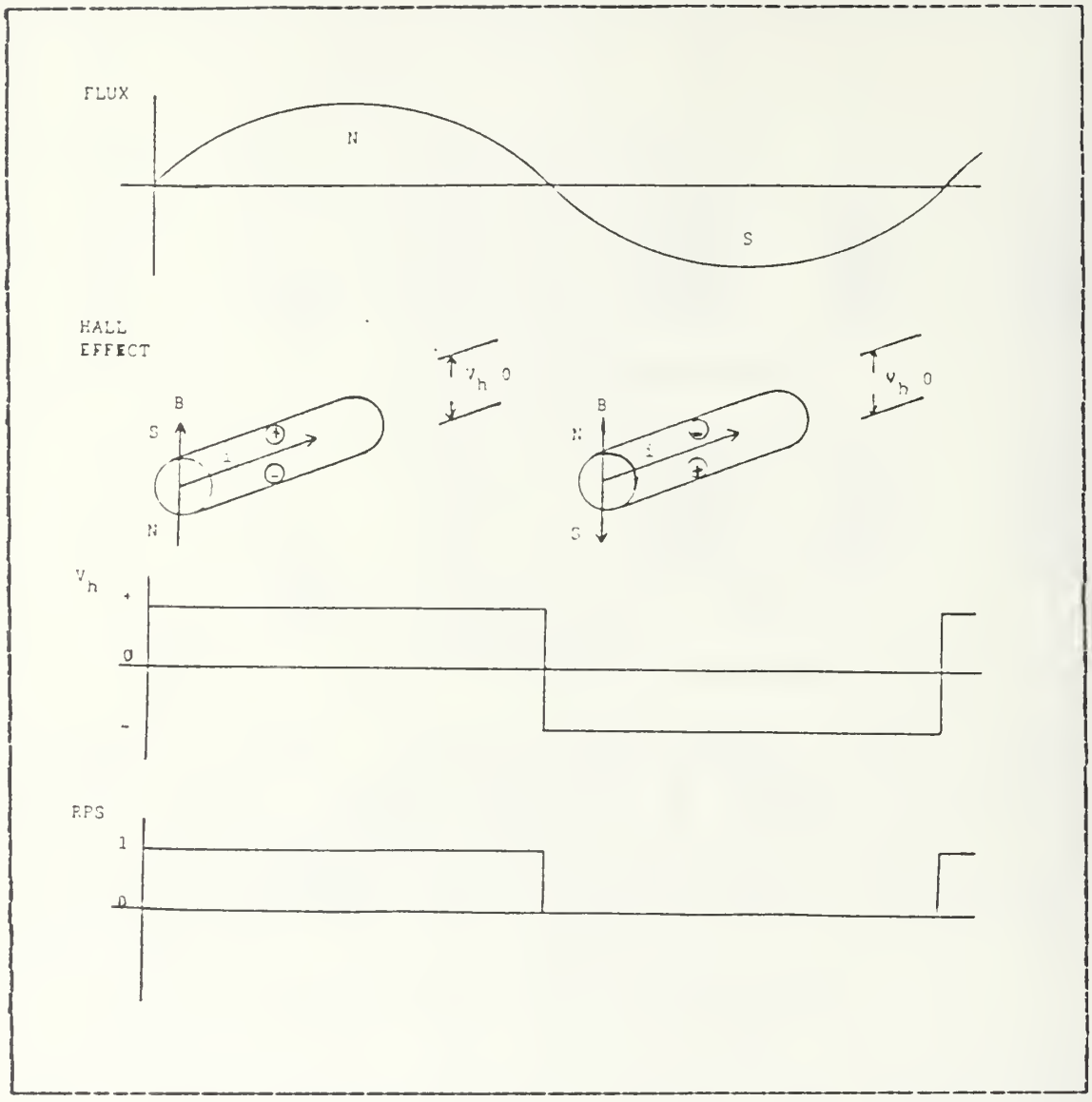

Figure 4.5 Sensor Logic Based on a Hall Effect Sensor

linear system, the principle of superposition is applicable and, thus, the torques developed by current flow through separate windings can be considered independently and then summed to give a total motor torque. Beyond this point, the brushless motor components are identical to its brush-type counterpart and behave similarly.

C. MODEL REVISION

CSMP modeling of this version of the brushless dc motor called for two modifications to the brush-type model. Essentially, a CSMP procedure function was constructed to act as a subroutine that embodies the logic of the switching action. The logic recognizes that if the motor shaft is within some degree range, for example 30 to 60 degrees, then it sets the appropriate rotor position sensors and energizes the switches for the appropriate two windings and deenergizes the switch for the third. In effect, only the forcing voltages are passed to the main program, whereas switch and sensor positions are available for output (see Appendix A).

V. VARIABLE FLUX

A. AIR GAP FLUX

The steady state behavior of both a brush-type and a brushless dc motor has been studied under the fundamental assumption that the back emf generated is a product of the shaft velocity times a constant, Kb (see Equation 2.2). Likewise, the motor torque is equated to the product of the current times a constant, Kt (see Equation 2.12). But as Equation 2.11 reveals in the case of the torque constant, Kt, the torque is in fact the product of some other constant of proportionality, Kt1, times the air gap flux, ϕ. The same is true for the back emf constant, Kb; that is, Kb is the product of some proportionality constant, Kb1, times the air gap flux, ϕ. In both cases, the flux, ϕ, has been assumed to be constant which is in agreement with the general practice when modeling permanent magnet dc motors. In point of fact, the flux is not constant but rather is distributed sinusoidally, generally being the sum of a sinusoid and one or more of its harmonics. How the motor is physically constructed determines this flux distribution. Two of the chief factors are the structure of the magnetic pole faces and, most importantly, how the windings are distributed in the armature. The latter includes such factors as the number of slots, the number of coils per slot and the spacing of the slots [Ref. 5]. The careful designer distributes the windings so as to minimize the effects of harmonics. Regardless of their constituents, these composite sinusoids have an average value, of course, and so in practice it is this average value that becomes the constant flux term, ϕ.

B. FLUX AS AN AVERAGE VALUE

A logical next step in the design of a more realistic model was the determination of an average value for the varible flux, ϕavg, and the corresponding proportionality constant, KK1 such that the ratio of ϕavg and KK1 equals one and the relationships of equations 2.2 and 2.5 are preserved. The equations for back emf, eb(t), and developed torque, tm(t), now become

$$eb(t) = Kbp * wm(t) \qquad \text{(eqn 5.1)}$$

$$tm(t) = Ktp * i(t) \qquad \text{(eqn 5.2)}$$

where the back emf constant, Kbp, and the torque constant, Ktp, are now expressed as

$$Kbp = Kb * (\phi avg/KK1) \qquad \text{(eqn 5.3)}$$

$$Ktp = Kt * (\phi avg/KK1) \qquad \text{(eqn 5.4)}$$

Assuming as a first approximation that the air gap flux varies as a simple sinusoid of unit magnitude, the first step toward finding the total system flux, ϕavg, was to determine the relationship of the individual flux patterns in each of the three phase windings. Analysis of a four-pole magnet rotating under three windings separated by 120 degrees (electrical) revealed the following relationships

$$\phi a = \sin(2\theta + \pi/6) \qquad \text{(eqn 5.5)}$$

$$\phi b = \sin(2\theta + 9\pi/6) \qquad \text{(eqn 5.6)}$$

$$\phi c = \sin(2\theta + 5\pi/6) \qquad \text{(eqn 5.7)}$$

where ϕa, ϕb and ϕc are the flux contributions of the respective phases. Returning to an earlier assumption that the circuit can be approximated as two windings in series, ignoring the third, then the average flux can also be approximated from the sum of the flux developed in two windings at a time. This approximation is further supported by the fact that the flux in the decay leg has, in fact, an average value of zero during every commutation interval. From the switching sequence of Figure 4.1, the two conducting legs were identified for each interval and, from Equations 5.5 through 5.7, their respective flux values calculated and summed. For every interval, the resulting flux waveshape was identical and had an average value of $\phi avg = 1.631$ (see Figure 5.1).

Since KK1 merely normalizes ϕavg, its value was easily determined to be KK1 = 0.613. The appropriate substitutions were then made in the CSMP model (see Appendix A for Revision Two). Since this amounted to nothing more than a rearrangement of constants, the model's output behavior remained unchanged. At this stage, the model simulates the behavior of a brushless dc motor being electronically commutated and exhibiting constant, steady state developed torque and motor speed due to a fixed, average value air gap flux.

C. SINUSOIDAL FLUX

The final stage of this thesis was to examine the steady state behavior of the brushless dc motor under variable air gap flux conditions. As a first approximation, the flux was modeled as a simple sinusoid and the flux relationships are those given in equations 5.5 through 5.7 As before, only the flux relating to the two conducting legs was considered. This composite variable flux, $\phi v1$, is shown in Figure 5.1 Equations 5.3 and 5.4 had to be modified to account for the different value of flux.

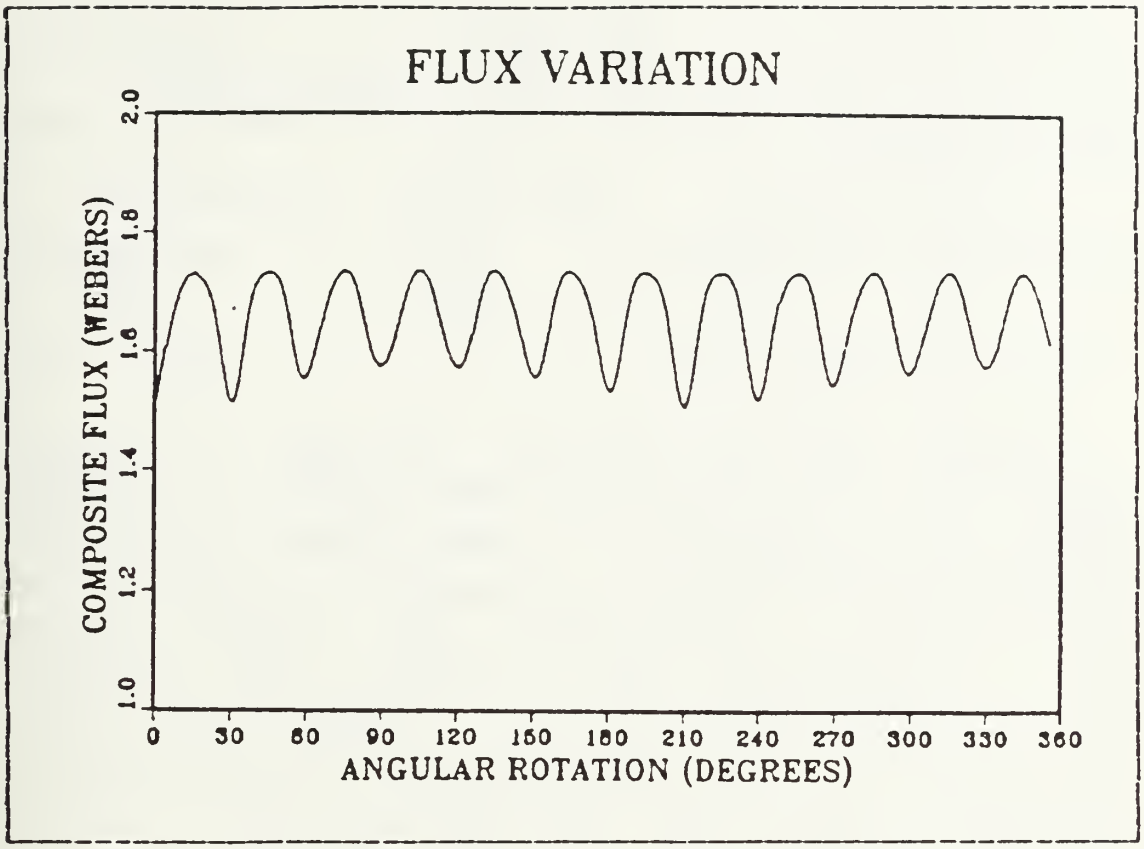

Figure 5.1 Composite Flux Variation for Two Windings

$$Kbpp = Kb * (\phi v1/KK2) \qquad \text{(eqn 5.8)}$$

$$Ktpp = Kt * (\phi v1/KK2) \qquad \text{(eqn 5.9)}$$

Recall that the objective was to keep the values of Kbpp and Ktpp as near as possible to those of Kb and Kt, respectively. In order to roughly normalize $\phi v1$, the constant value was determined as KK2 = 1.655. Since $\phi v1$ was now a variable quantity, it should be recognized that Kbpp and Ktpp were no longer strictly constants and were better expressed as the follcwing functions.

$$Kbpp = Kb(\phi v1) \qquad \text{(eqn 5.10)}$$

$$Ktpp = Kt(\phi v1) \qquad \text{(eqn 5.11)}$$

The equations for back emf, eb(t), and developed torque, tm(t), now became

$$eb(t,\phi v1) = Kbpp * wm(t) \qquad \text{(eqn 5.12)}$$

$$tm(t,\phi v1) = Ktpp * i(t) \qquad \text{(eqn 5.13)}$$

Because the total flux was no longer a constant, average value, it was expected that variation in developed torque (and, consequently, in motor speed) would result. Furthermore, as the system block diagram of Figure 2.1 indicates, torque is converted by the motor transfer function into a rotational speed. This is a process that is equivalent to inertia filtering of the torque ripple that results from variable flux. For the purposes of this thesis, ripple is defined as the ratio of the amount of variation from the maximum to the maximum itself. Having made the appropriate substitutions in the model (see Appendix A for Revision Three), the program was run under no-load conditions. It was observed that there was, in fact, ripple in both the developed torque and motor speed and that some inertia filtering did occur. The next logical step was to load the motor and study the effect on torque and speed ripple. Table III indicates that under no-load conditions where speed was highest, the percentage of ripple in the output speed was at a minimum but that torque ripple was at a maximum.

It can be seen that as the load increased the amount of ripple in the developed torque decreased from about 84% to 8%. A closer examination of the torque behavior under varying loads revealed that, even as the motor torque necessarily grew with increasing loads, in every case there was

TABLE III

Torque and Speed Ripple Due to Sinusoidal Flux

MOTOR LOAD (oz-in)	MOTOR SPEED (RPM)	% RIPPLE TORQUE	% RIPPLE SPEED
0.0	2557	83.9	1.1
32.0	2087	21.1	1.6
64.0	1617	12.2	2.6
96.0	1147	7.8	4.6

approximately a constant 8-9 oz-in variation. This variation can be attributed primarily to the flux variation in Ktpp and to a lesser degree to the variation in i(t) caused by the variation in back emf. Thus the magnitude of torque variation remained about the same for all loads though the percentage ripple appears to indicate otherwise. In the case of motor speed, the amount of ripple appeared to increase slightly with increasing load and thus decreasing speed. In this instance, the magnitude of variation did increase a small amount with decreasing speed - from 28 rpm at no-load to 52 rpm at 96 oz-ins - and suggests that speed ripple, at least, is somewhat dependent on load. This is due in part to the fact that as the motor slows, there is less rotor momentum and thus less inertia filtering. In addition, at slower speeds there are less frictional effects which at higher speeds also tend to filter out ripple. In general, it makes intuitive sense that at higher speeds frequency variations are harder to discern than at slower speeds.

D. HARMONIC FLUX

Having observed the effects of simple sinusoidal flux variation, the next step was to replace the single sinusoid with a flux composed of the sum of a sinusoid and its harmonics which is more representative of the air gap flux

patterns in an actual motor. The back emf of a typical commercial brushless dc motor is given in Figure 5.2 where the voltage between two terminals was measured with the motor rotating at 1200 rpm.

A harmonics analysis of this waveshape shows that the principle harmonic was the fifth and that the waveshape was closely described by the expression

$$3.0 \sin(\theta) + 0.59 \sin(5\theta) \qquad \text{(eqn 5.14)}$$

When substituted into equations 5.5 thru 5.7, and the different angular speed taken into account, the following relationships for flux result

$$\phi a = 3.0*\sin(2\theta+\pi/6) + 0.59*\sin(10\theta+5\pi/6) \qquad \text{(eqn 5.15)}$$

$$\phi b = 3.0*\sin(2\theta+9\pi/6) + 0.59*\sin(10\theta+9\pi/6) \qquad \text{(eqn 5.16)}$$

$$\phi c = 3.0*\sin(2\theta+5\pi/6) + 0.59*\sin(10\theta+\pi/6) \qquad \text{(eqn 5.17)}$$

The same procedures used in the simple sinusoid model were then applied to the harmonics case where the composite flux changes to $\phi v2$, a flux factor that varied to a slightly greater degree than did $\phi v1$. Equations 5.8 and 5.9 had to be modified as follows

$$Kbppp = Kb * (\phi v2/KK3) \qquad \text{(eqn 5.18)}$$

$$Ktppp = Kt * (\phi V2/KK3) \qquad \text{(eqn 5.19)}$$

where KK3 approximately normalizes the flux and had the value KK3 = 5.38. As before, Kbppp and Ktppp varied with the flux and so the new equations for back emf and developed torque became

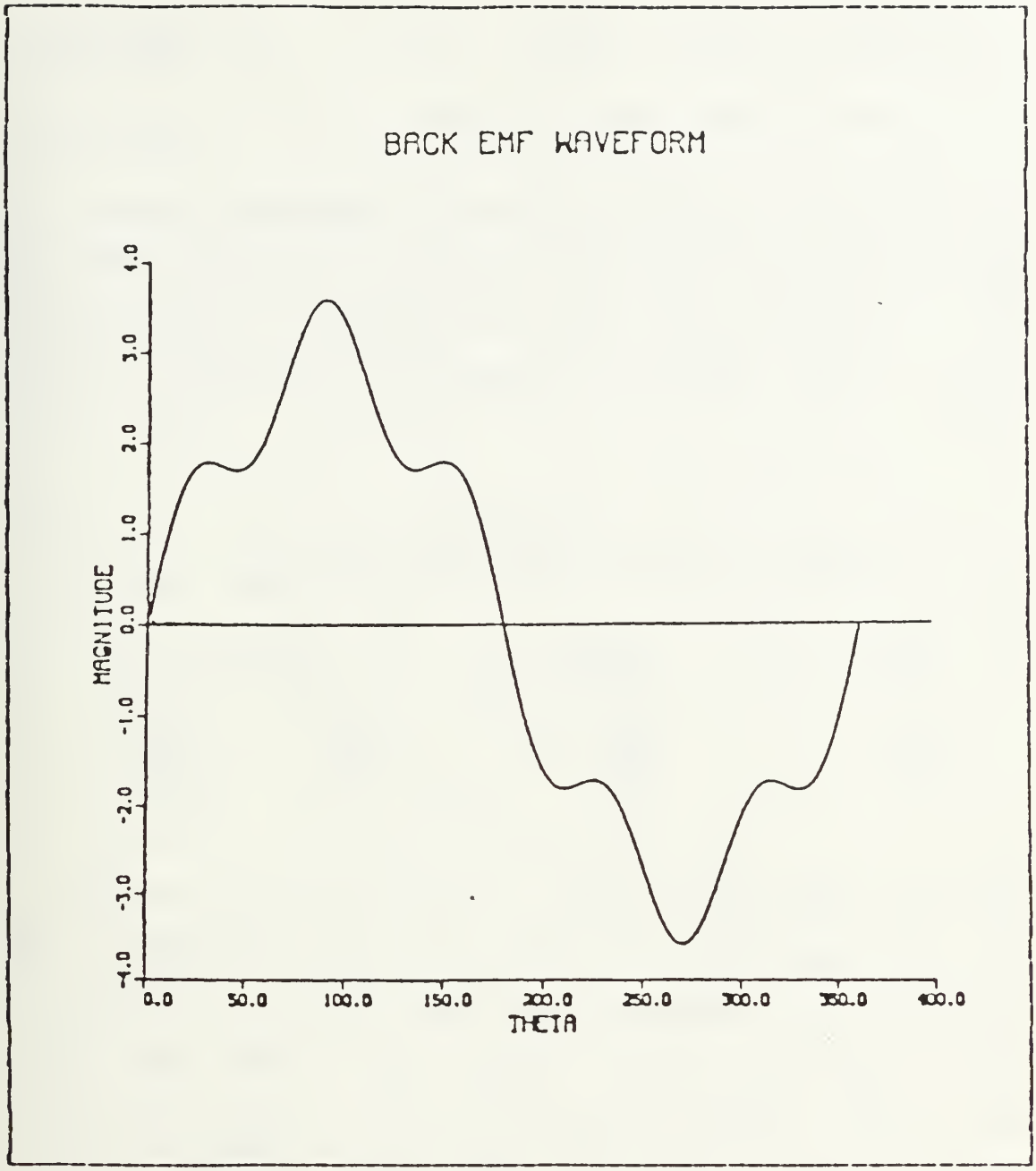

Figure 5.2 Back EMF Waveform Due to Harmonic Flux

$$eb(t,\phi v2) = Kb(\phi v2) * wm(t) \qquad \text{(eqn 5.20)}$$

$$eb(t,\phi v2) = Kbppp * wm(t) \qquad \text{(eqn 5.21)}$$

$$tm(t,\phi v2) = Kt(\phi v2) * i(t) \qquad \text{(eqn 5.22)}$$

$$tm(t,\phi v2) = Ktppp * i(t) \qquad \text{(eqn 5.23)}$$

The appropriate substitutions were once more made in the model (see Appendix A for Revision Four) and the model was run under various loads. As anticipated, the variable flux, $\phi v2$, produced ripple in the developed torque and motor speed. Table IV shows the resultant values for various loads.

TABLE IV

Torque and Speed Ripple Due to Harmonic Flux

MOTOR LOAD (oz-in)	MOTOR SPEED (rpm)	% RIPPLE TORQUE	% RIPPLE SPEED
0.0	2557	94.6	2.4
32.0	2087	38.5	3.7
64.0	1617	22.5	5.6
96.0	1147	14.7	9.8

Comparing Tables III and IV, it can be seen that the values for torque and speed ripple are of similar magnitudes. The somewhat higher values for torque are due to the fact that in the $\phi v2$ case there was a 16-21 Oz-in variation as opposed to an average 8-9 oz-in variation in the $\phi v1$ case. The speed ripple behavior was much like the $\phi v1$ case with proportionate increases resulting from the increased torque ripple. Thus, for both torque and speed ripple due to $\phi v2$, the model performed as expected; that is, slightly higher values of ripple occurred which were clearly attributable to the increased variability of the flux pattern of composite sinusoidal harmonics.

An important observation made during runs of the $\phi v1$ model came as a consequence of the motor speed variability,

particularly when the motor was unloaded. Since no-load speed was a function of Kb as given in equation 3.4, the variable Kbpp had the effect of increasing the upper-end speed beyond the 2557 rpm baseline given in Figure 3.1 This increased magnitude coupled with the swing of speed values created an undesirable effect in the unloaded condition. In effect, at certain points in time the additional speed produced back emf values that exceeded the input voltage which in turn resulted in negative current and developed torque values. Though these were transient negative values and had small effect on the steady state operation of the motor, still their presence was obviously unrealistic. The solution to returning the motor to all positive values of current and torque was to increase the friction filtering effect by adjustment of the viscous friction coefficient, Bm. It will be recalled from Chapter Three that a value for the Bm of the commercial motor being modelled was not available and that for the basic model a value for Bm was derived from the curve fitting process. Thus, it seemed reasonable and permissable to repeat the procedure here.

Since it makes sense that increasing the friction within a system will slow the system down, in this case increasing the value of Bm did just that. By increasing Bm from 0.00015 to 0.045 oz-in/rad/s, the upper-end of the motor speed was reduced to a value that eliminated the undesirable negative values. This caused the no-load speed to be lowered slightly below the desired value of 2557 rpms. Recalling that no-load speed is fixed by the back emf constant, Kb, this parameter was adjusted from 0.1120 to 0.1089 volt/rad/s to bring the back up to speed. Since this adjustment was less than 3% and the manufacturer specifications allowed a 10% +/- measurement error margin, this adjustment to Kb was permissable. Of course, a proportionate adjustment to the torque constant, Kt, was also made

since Kt and Kb must maintain a constant relationship as explained in Chapter Three. The effect on motor speed ripple was neglible. Reviewing the $\phi v2$ model at this point revealed that similar behavior in the no-load state occurred but on a larger scale due to the greater variability of $\phi v2$. A similar set of adjustments was necessary to eliminate the negative current and torque values in the unloaded condition. It required an adjustment of Bm from 0.00015 to 0.045 oz-in/rad/s in order to ensure that all values were positive. In addition, the back emf constant, Kb, was adjusted to 0.1192 volt/rad/s and a proportionate adjustment to Kt was made. Again, all adjustments were within tolerances.

Of course, it was earlier established in Equation 3.7 that changes to Kb and Kt would change the slope of the speed-torque curve. Thus, in both cases the slope was returned to its original value by adjusting the motor resistance, R. In the case of sinusoidal variable flux, R was reduced from 2.74 to 2.70 ohms. For harmonic variable flux, R was increased from 2.74 to 3.0 ohms. Again, both adjustments were within the 10% +/- allowable deviation. It was also observed that since both Kb and Kt no longer remained constant but rather varied within small ranges, the slope was not constant and varied accordingly in both the $\phi v1$ and $\phi v2$ models with the greatest change occurring when Kb and Kt simultaneously reached the minimum values of their respective ranges. Bearing in mind that these deviations in slope are fairly transient, their average values are most important and are the approximate values from which the final adjustments to R were based.

VI. SUMMARY

A. REMARKS AND CONCLUSIONS

CSMP language is a convenient tool for modeling a brushless DC motor. Positional sensor feedback and switching logic being functions of time, the action of electronic commutation can be nicely simulated in CSMP. The model can be fairly easily modified in order to study other motor configurations. For example, the three-phase star configuration used in this thesis could easily be changed to a grounded neutral, point D in figure 4.1, and the same types of analysis performed. In future studies where the complexity of the model is increased in order to include more design detail, the advantage of CSMP will become even more apparent.

In the course of simulating the effects of different air gap flux variations, it appeared necessary to make minor parameter adjustments in order to offset the feedback effects of torque and speed ripple. Within the scope of this thesis, adjusting the steady state performance was reasonable and justifiable. In a larger context, however, various control systems, particularly torque generation controllers, are specifically designed to reduce torque ripple and its effects. So, in at least one sense, these adjustments were somewhat artificial. To the extent that parameter adjustment is necessary and desirable, it must be understood that this is not a simple procedure since adjustment of one parameter almost always requires adjustment of one or more others. These adjustments in turn necessitate readjustment of the original parameter. The process is thus an iterative one. This model permits this kind of parameter

adjustment, but it is a long and tedious process that would be better performed by some sort of optimization algorithm.

B. RECOMMENDATIONS FOR FUTURE STUDY

The simulation of ripple effects is particulary relevant to the control engineer who must design the control circuitry and power conditioner to meet specific performance requirements. This points to several areas for future study. One area is the control of torque generation and the several principle configurations used in brushless DC motors. Two commonly used methods are the sinusoidal torque generation principle and the trapezoidal torque scheme. [Ref. 5]. In addition to torque generation control, a second area for investigation is power control of brushless DC motors. In this thesis, output power was unregulated and was studied simply as a function of a constant input voltage. In practice, however, power is produced and controlled by varying the supply voltage. Various schemes exist for power control; amoung these are linear transistor control and pulse-width or pulse-frequency control. [Ref. 5].

A very important area that this thesis did not address was that of the switching transients that occur as a consequence of commutation. During each switching interval, each winding is an inductor that stores energy which causes a significant amount of current to flow at the instant of switching. This can have serious effects, especially if breakdown conditions exist amoung the commutation transistors and other control circuit elements. In this same area, switching transients also occur within the control circuitry itself. Thus, a thorough investigation and understanding of the behavior of power transistors, diodes and other control elements used with electronic commutation needs to be done.

APPENDIX A
LISTING OF MODEL PROGRAMS

A. BASIC PROTOTYPE MODEL

The program in this section is a basic program that simulates the action of a standard brush-type DC motor. It is the prototype from which the brushless DC motor model and its several revisions are derived.

```
//THCCSMP1 JCE (2672,0116),'THOMAS-LAB6',CLASS=C
//*MAIN ORG=NPGVM1.2672P
//  EXEC CSMPXV
//X.CCMPRINT DD DUMMY
//X.SYSPRINT DD DUMMY
//X.SYSIN DD *

* VERSION ONE -- THIS IS THE BASIC PROGRAM THAT SIMULATES A
*                STANDARD BRUSH-TYPE DC MCTOR.  IT IS THE
*                PROTCTYPE FROM WHICH ALL LATER BRUSHLESS
*                DC MOTOR MODELS ARE DERIVED.

INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL =0.0, ...
 N = 1.0, JM = 0.001, KB = .112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.74, ...
 TL = (0.0, 32.0,64.0,96.0,128.0)


* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR
*       (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU
*        REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* TL -- LOAD TORQUE (OZ-IN)
* A1 = LA/RA  --  THE ELECTRICAL TIME CONSTANT OF THE MOTOR
* A2 = JM/BM  --  THE MECHANICAL TIME CONSTANT OF THE MOTOR


NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  B = BM + BLP
  J = JM + JLP
  A1 = LA / RA
  A2 = JM / BM
  THRST = 0.0
  JFAC = 0.0
```

```
DYNAMIC
  VI = 30.0 * STEP(0.0)
  VIN1 = VI - VEMF
  VIN2 = VIN1 * (1.0/RA)
  IM = REALPL(0.0,A1,VIN2)
  TM = IM * KT
  TN2 = TN1 * (1.0/BM)
  WM = REALPL(0.0,A2,TN2)
  WMRPM = WM * (30.0/PI)
  VEMF = WM * KB
  THETA = INTGRL(0.0,WM)
  PWR =  WM * TM * .0070615

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING
* THE MOTOR'S DIRECTION

PROCEDURE TN1=FWDBWD(VIN,TM,TL)
  IF(VIN.LT.0.0) GO TO 10
     TN1 = TM - TL
     GO TO 15
 10  TN1 = TM + TL
 15  CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.

PROCEDURE THRST=RESET(JFAC,THDEG)
     TS = JFAC * 360.0
     THRST = THDEG - TS
     IF(THRST.LT.360.0) GO TO 40
     JFAC = JFAC + 1.0
 40  CONTINUE
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .04, OUTDEL = 0.0004, PRDEL = 0.0004
  PRINT VEMF, IM, TM, WM, WMRPM, PWR
  PAGE MERGE
       END
       STOP
ENDJOB
/*
```

B. REVISION ONE

This is the first revision of the basic prototype. This model simulates the switching logic of a brushless DC motor which is based on feedback from Hall effect sensors. In addition, the windings are treated independently and their contributions to developed torque are superposed. Since the superposition results in twice as much current flow as a single lumped coil, the total current is halved to retain the same overall motor behavior as in the prototype.

```
//THCCSMP2 JCE (2672,0116),'THOMAS-LAB6',CLASS=C
//*MAIN CRG=NFGVM1.2672P
// EXEC CSMPXV
//X.COMPRINT DD DUMMY
//X.SYSPRINT DD DUMMY
//X.SYSIN DD *

* VERSION TWC -- THIS IS THE FIRST REVISION OF THE BASIC PROTOTYPE.  THIS
*                MODEL SIMULATES THE SWITCHING LOGIC OF A BRUSHLESS DC
*                MOTOR WHICH IS BASED ON FEEDBACK FROM HALL EFFECT
*                SENSORS AS DESCRIBED IN CHAPTER FOUR.  IN ADDITION,
*                THE WINDINGS ARE TREATED INDEPENDENTLY AND THEIR
*                CONTRIBUTIONS TO DEVELOPED TORQUE ARE TREATED AS
*                SUPERPOSABLE.  SINCE THE SUPERPOSITION RESULTS IN
*                TWICE AS MUCH CURRENT FLOW AS A SINGLE LUMPED COIL,
*                THE TOTAL CURRENT IS HALVED IN ORDER TO KEEP THE
*                OVERALL BEHAVIOR THE SAME AS IN VERSION ONE.

INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
  JM = 0.001, KB = 0.112, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.740, TL = (0.0,32.,64.,96.,128)

* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLF -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLF -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* A1 = LA/RA   --  THE ELECTRICAL TIME CONSTANT OF THE MOTOR
* A2 = J/B     --  THE MECHANICAL TIME CONSTANT OF THE MOTOR

NOSORT
  BLF = BL/(N**2)
  JLF = JL/(N**2)
  J = JM + JLF
  B = BM + BLF
  A1 = LA / RA
  A2 = J / B
```

```
      THRST = 0.C
      JFAC = 0.0

    DYNAMIC
      VIF= 30.0 * STEP(0.0)
      VIB = C.O
      VIN = VIF + VIB
      VIN1 = VIN - VEMF
      VIN2 = VIN1 * (1.0/RA)
      IMA = REALPL(0.0,A1,VA)
      IME = REALPL(0.0,A1,VB)
      IMC = REALPL(0.C,A1,VC)
      IMT = (IMA + IME + IMC)/2
      TM = IMT * KT
      TN2 = TN1 * (1.C/B)
      WM = REALPL(0.0,A2,TN2)
      WMRPM = WM * (3C./PI)
      WMRPMR = WMRPM/N
      VEMF = WM * KB
      THETA = INTGRL(C.0,WM)
      THDEG = THETA * (180.0/PI)
      THCON = THRST
      PWR = WM * TM * .0070615

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.

    PROCEDURE TN1=FWDEWD(VIN,TM,TL)
      IF(VIN.LT.C.C) GO TO 10
        TN1 = TM - TL
        GO TO 15
     10 TN1 = TM + TL
     15 CONTINUE
    ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.

    PROCEDURE THRST=RESET(JFAC,THDEG)
        TS = JFAC * 360.0
        THRST = THDEG - TS
        IF(THRST.LT.360.0) GO TO 40
```

```
      JFAC = JFAC + 1.0
   40 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE SERVES SEVERAL PURPOSES.  FIRST, IT PROVIDES THE MODEL A
* MEANS OF APPLYING THE PROPER VOLTAGE TO THE APPROPRIATE WINDINGS WHICH
* SIMULATES GENERAL COMMUTATION.  SECOND, IT SETS THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.

PROCEDURE VA,VB,VC,SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON,VIN2)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45   THCON = THCON - 180.
46 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50  VA =  0.0
     VB =  VIN2
     VC =  VIN2
     SE1 = 1.
     SE2 = 0.
     SE3 = 1.
     SW1 = 0.
     SW2 = 0.
     SW3 = 0.
     SW4 = 1.
     SW5 = 1.
     SW6 = 0.
     GO TO 60
 51  VA =  VIN2
     VB =  VIN2
     VC =  0.0
     SE1 = 1.
     SE2 = 0.
     SE3 = 0.
     SW1 = 1.
     SW2 = 0.
     SW3 = 0.
```

```
52
SW4 = 1...
SW5 = 00..
SW6 = 00..
GC TC 60 VIN2
VA = 00.. 0.CC
VB = 00.. VIN2
VC = 11..
VE1 = 11..
VE2 = 10..
VE3 = 10..
SW1 = 00..
SW2 = 00..
SW3 = 00..
SW4 = 00..
SW5 = 00..
SW6 = 00..
GC TC 60 VIN2
VA = 00.. 0.CC
VB = 00.. VIN2
VC = 11..
VE1 = 11..
VE2 = 10..
VE3 = 10..
SW1 = 00..
SW2 = 00..
SW3 = 00..
SW4 = 00..
SW5 = 00..
SW6 = 00..
GC TC 60 VIN2
VA = 00.. 0.CC
VB = 00.. VIN2
VC = 11..
VE1 = 11..
VE2 = 10..
VE3 = 10..
SW1 = 00..
SW2 = 00..
SW3 = 00..
SW4 = 00..
SW5 = 00..
SW6 = 00..
GC TC 60 VIN2
VA = 00.. 0.CC
VB = 00.. VIN2
VC = 11..
VE1 = 11..
VE2 = 10..
VE3 = 10..
SW1 = 00..
SW2 = 00..
SW3 = 00..
SW4 = 00..
SW5 = 00..
SW6 = 00..
GC TC 60 VIN2
VA = 00.. 0.CC
VB = 00.. VIN2
VC = 11..
VE1 = 11..
VE2 = 10..
53
54
55
```

```
      SE3 = 1.
      Sw1 = 0.
      Sw2 = 1.
      Sw3 = 0.
      Sw4 = 0.
      Sw5 = 1.
      Sw6 = 0.
      GC TC 60
 60 CONTINUE
ENDPRCCEDURE


TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .0004, PRDEL = .0004
  PRINT THRST,VEMF,IMA,IMB,IMC,IMT,TM,wM,hMRPM
* PRINT SE1, SE2, SE3, Sw1, Sw2, Sw3, Sw4, Sw5, Sw6
  LABEL MOTOR SPEED DUE TO STEP INPUT
  PAGE MERGE

*  PAGE XYPLOT
       END
       STOP
ENDJOB
/*
```

C. REVISION TWO

In the following program, the motor's air gap flux is treated as the average value of the sum of the flux acting in two windings as explained in Chapter Five. For convenience of study, both windings are again lumped into a single winding as in the prototype. This facilitates a closer focussing on the effects of variable flux on motor behavior.

```
//THCCSMP2 JCE (2672,0116),'THOMAS-LAB6',CLASS=C
//*MAIN CRG=NFGVM1.2672P
// EXEC CSMPXV
//X.CCMPRINT DD DUMMY
//X.SYSPRINT DD DUMMY
//X.SYSIN DD *

* VERSION THREE - THIS PURPOSE OF THIS PROGRAM IS TO TREAT THE AIR GAP
* FLUX AS THE AVERAGE VALUE OF THE SUM OF THE FLUX ACTING IN TWO
* WINDINGS AS EXPLAINED IN CHAPTER FIVE.  FOR CONVENIENCE OF STUDY, BOTH
* WINDINGS ARE LUMPED INTO ONE WINDING AS IN VERSION ONE IN ORDER TO
* FACILITATE CLOSE STUDY OF THE EFFECTS OF VARIABLE FLUX ON MOTOR
* BEHAVIOR.

INITIAL
CONSTANT KT = 15.9, BM = 0.00015, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.112, PI = 3.14159265, PHIAVG = 1.631, KK1 = 1.631
PARAMETER LA = .0016, RA = 2.740, ...
          TL = (0.0,32.0,64.0,96.0,128.0)

* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* TL -- LOAD TORQUE (OZ-IN)
* A1 = LA/RA  --  THE ELECTRICAL TIME CONSTANT OF THE MOTOR
* A2 = J/B    --  THE MECHANICAL TIME CONSTANT OF THE MOTOR
* KBP - THE NORMALIZED PRODUCT OF KB AND PHIAVG
* KTP - THE NORMALIZED PRODUCT OF KT AND PHIAVG
* PHIAVG -- THE AVERAGE VALUE OF SINUSOIDALLY VARYING FLUX

NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
```

```
      A2 = J / B
      THRST = 0.0
      JFAC = 0.0
      KTF = KT * FFIAVG * (1/KK1)
      KBF = KB * FFIAVG * (1/KK1)

    DYNAMIC
      VIF= 30.0 * STEP(0.0)
      VIB = 0.0
      VIN = VIF + VIB
      VIN1 = VIN - VEMF
      VIN2 = VIN1 * (1.0/RA)
      IMF = REALPL(0.0,A1,VIN2)
      TM = KTF * IMF
      TN2 = TN1 * (1.0/B)
      WM = REALPL(0.0,A2,TN2)
      WMRPM = WM * (30./PI)
      WMRPMR = WMRPM/N
      THETA = INTGRL(0.0,WM)
      THDEG = THETA * (180.0/PI)
      THCON = THRST
      PWR = WM * TM * .0070615
      VEMF = KBF * WM

    * THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
    * DIRECTION.

    PROCEDURE TN1=FWDBWD(VIN,TM,TL)
      IF(VIN.LT.0.0) GO TO 10
        TN1 = TM - TL
        GO TO 15
     10 TN1 = TM + TL
     15 CONTINUE
    ENDPROCEDURE

    * THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
    * OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
    * SWITCHING AND POSITION SENSING ACTION.

    PROCEDURE THRST=RESET(JFAC,THDEG)
        TS = JFAC * 360.0
        THRST = THDEG - TS
        IF(THRST.LT.360.) GO TO 40
```

09

```
      JFAC = JFAC + 1.0
   40 CONTINUE
ENDPROCEDURE

* THE PURPOSE OF THIS PROCEDURE IS TO SET THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0.  THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.

PROCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
   50 SE1 = 1.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   51 SE1 = 1.
      SE2 = 0.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   52 SE1 = 1.
      SE2 = 1.
      SE3 = 0.
      SW1 = 1.
```

```
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 53   SE1 = 0.
      SE2 = 1.
      SE3 = 0.
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 54   SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
 60   CONTINUE
ENDPROCEDURE

TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .0004, PRDEL = .0004
  PRINT IFRST,VEMF,IMP,TM,WM,WMRPM,PWR
  PAGE MERGE
       END
       STOP
ENDJOB
/*
```

D. REVISION THREE

The purpose of this version of the program is treat the air gap flux as varying in simple sinusoidal fashion. The total system flux is treated as the algebraic sum of the flux developed in the two active windings.

```
//THCCSMF2 JCE (2672,0116),'THOMAS-LAB6',CLASS=C
//*MAIN CRG=NFGVM1.2672P
//  EXEC CSMPX\
//X.COMPRINT DD DUMMY
//X.SYSPRINT DD DUMMY
//X.SYSIN DD *


* VERSION FOUR -- THE PURPOSE OF THIS VERSION OF THE PROGRAM IS TO
* TREAT THE AIR GAP FLUX AS VARYING IN SINUSOIDAL FASHION. THE TOTAL
* SYSTEM FLUX IS TREATED AS THE ALGEBRAIC SUM OF THE FLUX DEVELOPED IN
* THE TWO ACTIVE WINDINGS AS EXPLAINED IN CHAPTER FIVE.


INITIAL
CONSTANT KT = 15.40, BM = 0.022, BL = 0.0, JL = 0.0, N = 1.0, ...
  JM = 0.001, KB = 0.1089, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.700, ...
          KK2= 1.6551, TL = (0.0,32.0,64.0,96.0,128.0)


* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLF -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLF -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* TL -- LOAD TORQUE (OZ-IN)
* A1 = LA/RA  --  THE ELECTRICAL TIME CONSTANT OF THE MOTOR
* A2 = J/B    --  THE MECHANICAL TIME CONSTANT OF THE MOTOR
* JFAC -- A COUNTER VARIELE
* KBFP -- THE NORMALIZED PRODUCT OF KB AND THE COMPOSITE VARIABLE FLUX
* KTFP -- THE NORMALIZED PRODUCT OF KT AND THE COMPOSITE VARIABLE FLUX


NOSORT
  BLF = BL/(N**2)
  JLF = JL/(N**2)
  J = JM + JLF
  B = BM + BLF
  A1 = LA / RA
  A2 = J / B
  THRST = 0.0
```

```
      JFAC = C.O

    DYNAMIC
      VIF= 3C.O * STEP(O.O)
      VIB = C.O
      VIN = VIF + VIB
      VIN1 = VIN - VEMF
      VIN2 = VIN1 * (1.O/RA)
      IMF = REALPL(O.O,A1,VIN2)
      TM = KTPP * IMP
      TN2 = TN1 * (1.O/B)
      wM = REALPL(C.O,A2,TN2)
      WMRPM = WM * (3C./PI)
      wMFPMR = wMFPM/N
      BEMFA = SIN(2.*THETA + (1 * PI/6))
      BEMFB = SIN(2.*THETA + (9 * PI/6))
      BEMFC = SIN(2.*THETA + (5 * PI/6))
      THETA = INTGRL(C.O,wM)
      THDEG = THETA * (180.O/PI)
      THCCN = THRST
      PWR = wM * TM * .0070615
      VEMF = KBPF * wM
      KBFP = KB * EEMFT * (1/KK2)
      KTFP = KT * EEMFT * (1/KK2)

    * THIS PRCCEDURE PROVICES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
    * DIRECTICN.

    PROCEDURE TN1=FWDEWD(VIN,TM,TL)
      IF(VIN.LT.O.O) GO TO 10
         TN1 = TM - TL
         GC TC 15
     10 TN1 = TM + TL
     15 CONTINUE
    ENDPROCEDURE

    * THIS PRCCEDURE RESETS THE VARIABLE THRST TC O AFTER EVERY 360 DEGREES
    * OF MECHANICAL RCTATICN.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
    * SWITCHING AND PCSITICN SENSING ACTICN.

    PROCEDURE THRST=RESET(JFAC,THDEG)
         TS = JFAC * 360.O
         THRST = THDEG - TS
```

```
      IF(THRST.LT.360.) GO TO 40
      JFAC = JFAC + 1.0
   40 CONTINUE
ENDPROCEDURE

* THE PURPOSE OF THIS PROCEDURE IS TO SET THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0. THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.

PROCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON)
   IF(THCON .GE.180.) GO TO 45
   GO TO 46
45   THCON = THCON - 180.
46 CONTINUE
   IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
   IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
   IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
   IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
   IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
   IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
   50 SE1 = 1.
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
   51 SE1 = 1.
      SE2 = 0.
      SE3 = 0.
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 1.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
   52 SE1 = 1.
      SE2 = 1.
      SE3 = 0.
```

```
      SW1 = 1.
      SW2 = 0.
      SW3 = 0.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 53   SE1 = 0.
      SE2 = 1.
      SE3 = 0.
      SW1 = 0.
      SW2 = 0.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 1.
      GO TO 60
 54   SE1 = 0.
      SE2 = 1.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 1.
      SW4 = 0.
      SW5 = 0.
      SW6 = 0.
      GO TO 60
 55   SE1 = 0.C
      SE2 = 0.
      SE3 = 1.
      SW1 = 0.
      SW2 = 1.
      SW3 = 0.
      SW4 = 0.
      SW5 = 1.
      SW6 = 0.
      GO TO 60
 60   CONTINUE
ENDPROCEDURE

* THE FOLLOWING PROCEDURE HAS THE SAME FORM AND EFFECT AS THE
* PREVIOUS.  IT IS USED HERE TO DETERMINE THE ALGEBRAIC SUM OF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE BACK EMF (BEMFT).  THIS FUNCTION COULD AS EASILY
* HAVE BEEN CALCULATED IN THE PREVIOUS PROCEDURE EXCEPT THAT
* THERE WAS INSUFFICIENT ROOM TO ACCOMODATE THE ADDITIONAL VARIABLES.
```

```
PROCEDURE BEMFT=VOLT(THCON,BEMFA,BEMFB,BEMFC)
  IF(THCON .GE.180.) GO TO 65
  GO TO 66
65  THCON = THCON - 180.
66 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 70
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 71
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 72
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 73
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 74
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 75
 70 BEMFT = BEMFA - BEMFB
    GO TO 80
 71 BEMFT = BEMFA - BEMFC
    GO TO 80
 72 BEMFT = BEMFB - BEMFC
    GO TO 80
 73 BEMFT = BEMFB - BEMFA
    GO TO 80
 74 BEMFT = BEMFC - BEMFA
    GO TO 80
 75 BEMFT = BEMFC - BEMFB
    GO TO 80
 80 CONTINUE
ENDPROCEDURE


TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .040, OUTDEL = .0004, PRDEL = .0004
* PRINT SE1, SE2, SE3, SW1, SW2, SW3, SW4, SW5, SW6
  PRINT THRST,BEMFT1,BEMFT,VEMF,IMP,TM,WM,WMRPM,PWR
  PAGE MERGE
       END
       STOP
ENDJOB
/*
```

E. REVISION FOUR

This version of the model treats the flux as varying according to the sum of a sinusoid of fundamental frequency and its fifth harmonic as explained in Chapter Five. The total flux is again approximated as the algebraic sum of the flux developed in two windings at a time.

```
//THOCSMP2 JOB (2672,0116),'THOMAS-LAB6',CLASS=C
//*MAIN ORG=NPGVM1.2672P
// EXEC CSMPX\
//X.COMPRINT DD DUMMY
//X.SYSPRINT DD DUMMY
//X.SYSIN DD *


* VERSION FIVE -- THE PURPOSE OF THIS VERSION OF THE PROGRAM IS TO
* TREAT THE FLUX AS VARYING ACCORDING TO THE SUM OF A SINUSOID OF
* FUNDAMENTAL FREQUENCY AND ITS FIFTH HARMONIC AS EXPLAINED IN CHAPTER
* FIVE.  THE TOTAL FLUX IS APPROXIMATED AS THE ALGEBRAIC SUM OF THE FLUX
* DEVELOPED IN TWO WINDINGS AT A TIME.


INITIAL
CONSTANT KT = 16.82, BL = 0.0, JL = 0.0, N = 1.0, ...
 JM = 0.001, KB = 0.11875, PI = 3.14159265
PARAMETER LA = .0016, RA = 2.624, ...
          KK3 = 5.3821, BM = .04500, TL = (0.0,32.,64.,96.)


* KT -- TORQUE CONSTANT (OZ-IN/AMP)
* KB -- BACK EMF CONSTANT (VOLT/RAD/S)
* RA -- RESISTANCE OF THE MOTOR (OHM)
* BM -- VISCOUS FRICTION COEFFICIENT OF THE MOTOR (OZ-IN/RAD/S)
* BL -- VISCOUS FRICTION COEFFICIENT OF THE LOAD
* BLP -- VISCOUS FRICTION COEFFICIENT OF LOAD THRU REDUCTION GEARS
* B -- TOTAL VISCOUS FRICTION OF THE MOTOR SYSTEM
* JM -- INERTIA OF THE MOTOR (OZ-IN/S-S)
* JL -- INERTIA OF THE LOAD
* JLP -- INERTIA OF THE LOAD THRU REDUCTION GEARS
* J -- TOTAL INERTIA OF THE MOTOR SYSTEM
* TL -- LOAD TORQUE (OZ-IN)
* A1 = LA/RA  --  THE INVERSE ELECTRICAL TIME CONSTANT
* A2 = J/B  --  THE INVERSE MECHANICAL TIME CONSTANT
* JFAC = COUNTER VARIABLE
* JFAC -- A COUNTER VARIBLE
* KBFPP -- THE NORMALIZED PRODUCT OF KB AND THE COMPOSITE VARIABLE FLUX
* KTFPP -- THE NORMALIZED PRODUCT OF KT AND THE COMPOSITE VARIABLE FLUX


NOSORT
  BLP = BL/(N**2)
  JLP = JL/(N**2)
  J = JM + JLP
  B = BM + BLP
  A1 = LA / RA
```

```
   A2 = J / B
   THRST = 0.0
   JFAC = 0.0

DYNAMIC
   VIF= 30.0 * STEP(0.0)
   VIB = 0.0
   VIN = VIF + VIB
   VIN1 = VIN - VEMF
   VIN2 = VIN1 * (1.0/RA)
   IMF = REALPL(0.0,A1,VIN2)
   TM = KTPPP * IMF
   TN2 = TN1 * (1.0/B)
   WM = REALPL(0.0,A2,TN2)
   WMRPM = WM * (30./PI)
   WMRPMR = WMRPM/N
   BEMFA =(3.*SIN(2.*THETA+(1*PI/6))+.59*SIN(10.*THETA+(5*PI/6)))
   BEMFB =(3.*SIN(2.*THETA+(9*PI/6))+.59*SIN(10.*THETA+(9*PI/6)))
   BEMFC =(3.*SIN(2.*THETA+(5*PI/6))+.59*SIN(10.*THETA+(1*PI/6)))
   THETA = INTGRL(0.0,WM)
   THDEG = THETA * (180.0/PI)
   THCON = THRST
   PWR = WM * TM * .00706155
   VEMF = KBPPP * WM
   KBPPP = KB * BEMFT * (1/KK3)
   KTPPP = KT * BEMFT * (1/KK3)

* THIS PROCEDURE PROVIDES A SIMPLE MECHANISM FOR REVERSING THE MOTOR'S
* DIRECTION.

PROCEDURE TN1=FWDREV(VIN,TM,TL)
   IF(VIN.LT.0.0) GO TO 10
      TN1 = TM - TL
      GO TO 15
  10 TN1 = TM + TL
  15 CONTINUE
ENDPROCEDURE

* THIS PROCEDURE RESETS THE VARIABLE THRST TO 0 AFTER EVERY 360 DEGREES
* OF MECHANICAL ROTATION.  THIS IS FUNDAMENTAL TO THE SIMULATION OF ALL
* SWITCHING AND POSITION SENSING ACTION.

PROCEDURE THRST=RESET(JFAC,THDEG)
```

```
  TS = JFAC * 360.0
  THRST = THDEG - TS
  IF(THRST.LT.360.) GO TO 40
    JFAC = JFAC + 1.0
  40 CONTINUE
ENDPROCEDURE


* THE PURPOSE OF THIS PROCEDURE IS TO SET THE VARIABLES SE1 THRU
* SE3 AND SW1 THRU SW6 TO LOGIC LEVELS 1 OR 0. THIS SIMULATES THE ACTION
* OF HALL EFFECT SENSORS BEING TURNED ON OR OFF IN THE FORMER CASE AND
* SIMULATES POWER TRANSISTORS BEING ENERGIZED OR SWITCHED OFF IN THE
* LATTER CASE.  THCON IS THE VARIABLE THROUGH WHICH THE SWITCHING LOGIC
* IS IMPLEMENTED.


PROCEDURE SE1,SE2,SE3,SW1,SW2,SW3,SW4,SW5,SW6=VOLT(THCON)
  IF(THCON .GE.180.) GO TO 45
  GO TO 46
45  THCON = THCON - 180.
46 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 50
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 51
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 52
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 53
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 54
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 55
 50  SE1 = 1.
     SE2 = 0.
     SE3 = 1.
     SW1 = 0.
     SW2 = 0.
     SW3 = 0.
     SW4 = 1.
     SW5 = 1.
     SW6 = 0.
     GO TO 60
 51  SE1 = 1.
     SE2 = 0.
     SE3 = 0.
     SW1 = 1.
     SW2 = 0.
     SW3 = 0.
     SW4 = 1.
     SW5 = 0.
     SW6 = 0.
     GO TO 60
 52  SE1 = 1.
```

```
      SSE2 = 1.
      SSE3 = 0.
      SSW1 = 1.
      SSW2 = 0.
      SSW3 = 0.
      SSW4 = 0.
      SSW5 = 0.
      SSW6 = 1.
      GO TO 60
 53   SSE1 = 0.
      SSE2 = 1.
      SSE3 = 0.
      SSW1 = 0.
      SSW2 = 0.
      SSW3 = 1.
      SSW4 = 0.
      SSW5 = 0.
      SSW6 = 1.
      GO TO 60
 54   SSE1 = 0.
      SSE2 = 1.
      SSE3 = 1.
      SSW1 = 0.
      SSW2 = 1.
      SSW3 = 1.
      SSW4 = 0.
      SSW5 = 0.
      SSW6 = 0.
      GO TO 60
 55   SSE1 = 0.0
      SSE2 = 0.
      SSE3 = 1.
      SSW1 = 0.
      SSW2 = 1.
      SSW3 = 0.
      SSW4 = 0.
      SSW5 = 1.
      SSW6 = 0.
      GO TO 60
 60   CONTINUE
ENDPROCEDURE

* THE FOLLOWING PROCEDURE HAS THE SAME FORM AND EFFECT AS THE
* PREVIOUS.  IT IS USED HERE TO DETERMINE THE ALGEBRAIC SUM OF
* THE VARIABLE FLUX COMPONENTS FOR USE IN COMPUTING THE MOTOR'S
* APPROXIMATE BACK EMF (BEMFT).  THIS FUNCTION COULD AS EASILY
* HAVE BEEN CALCULATED IN THE PREVIOUS PROCEDURE EXCEPT THAT IT
```

```
* COULD NOT ACCOMODATE THE ADDITIONAL VARIABLES.

PROCEDURE BEMFT=VOLT(THCON,BEMFA,BEMFB,BEMFC)
  IF(THCON .GE.180.) GO TO 65
  GO TO 66
65  THCON = THCON - 180.
66 CONTINUE
  IF(THCON .GE.  0..AND. THCON .LT. 30.) GO TO 70
  IF(THCON .GE. 30..AND. THCON .LT. 60.) GO TO 71
  IF(THCON .GE. 60..AND. THCON .LT. 90.) GO TO 72
  IF(THCON .GE. 90..AND. THCON .LT.120.) GO TO 73
  IF(THCON .GE.120..AND. THCON .LT.150.) GO TO 74
  IF(THCON .GE.150..AND. THCON .LT.180.) GO TO 75
 70 BEMFT = BEMFA - BEMFB
    GO TO 80
 71 BEMFT = BEMFA - BEMFC
    GO TO 80
 72 BEMFT = BEMFB - BEMFC
    GO TO 80
 73 BEMFT = BEMFB - BEMFA
    GO TO 80
 74 BEMFT = BEMFC - BEMFA
    GO TO 80
 75 BEMFT = BEMFC - BEMFB
    GO TO 80
 80 CONTINUE
ENDPROCEDURE


TERMINAL
  TITLE BASIC DC MOTOR SYSTEM
  TIMER FINTIM = .028, OUTDEL = .0004, PRDEL = .0004
* PRINT THRST, SE1, SE2, SE3
* PRINT SW1, SW2, SW3
  PRINT SW4, SW5, SW6
* PRINT VEMF,IMF,TM,WMRPM,PWR
  LABEL MOTOR SPEED DUE TO STEP INPUT
  PAGE MERGE
       END
       STOP
ENDJOB
/*
```

APPENDIX B
SAMPLE OUTPUT

The following is a sample of the type of information the model can provide. In this particular case, the fourth revision of the basic prototype, the harmonic flux case, was used. For completeness, the motor was run at loads from 0.0 up through 96.0 oz-in, which was the range of loads with which all analysis was performed. In addition to such motor variables as speed, current and power, a sampling of the feedback from Hall effect sensors as well as the switching action of the power transistors is included.

0 TL = 0

TIME	VEMF	IMP	TM	WMRPM	PWR
.0	.0	.0	.0	.0	.0
4.000000D-04	2.3847	5.3208	89.541	191.67	12.691
8.000000D-04	7.4984	7.3252	122.88	604.59	54.939
1.200000D-03	12.900	7.3655	120.84	1063.5	95.037
1.600000D-03	16.682	6.5380	100.59	1466.6	109.09
2.000000D-03	18.294	5.6449	78.568	1777.8	103.29
2.400000D-03	19.436	4.9736	64.909	2014.4	96.690
2.800000D-03	22.632	4.2362	58.644	2211.3	95.897
3.200000D-03	27.929	3.0190	47.973	2377.3	84.337
3.600000D-03	30.728	1.5752	26.429	2477.1	48.412
4.000000D-03	27.827	.91961	13.829	2503.0	25.595
4.400000D-03	24.505	1.2580	16.592	2513.1	30.835
4.800000D-03	25.695	1.6190	22.131	2542.5	41.609
5.200000D-03	30.333	1.1683	18.587	2578.8	35.444
5.600000D-03	31.879	.28830	4.8236	2577.2	9.1926
6.000000D-03	27.816	.17474	2.5887	2539.5	4.8614
6.400000D-03	24.432	.89361	11.718	2520.1	21.837
6.800000D-03	25.978	1.4056	19.474	2536.2	36.523
7.200000D-03	30.518	1.0047	16.180	2563.2	30.667
7.600000D-03	31.441	.23142	3.8523	2554.7	7.2775
8.000000D-03	27.231	.25170	3.6815	2518.2	6.8555
8.400000D-03	24.210	1.0076	13.174	2504.4	24.398
8.800000D-03	26.119	1.4650	20.493	2525.6	38.274
9.200000D-03	30.646	1.0038	16.285	2554.9	30.768
9.600000D-03	31.206	.24351	4.0361	2546.5	7.6005
1.000000D-02	26.919	.31548	4.5720	2512.4	8.4942
1.040000D-02	24.154	1.0746	14.031	2502.2	25.962
1.080000D-02	26.339	1.4796	20.868	2525.9	38.980
1.120000D-02	30.832	.96788	15.798	2555.0	29.848
1.160000D-02	31.042	.22564	3.7232	2544.6	7.0059
1.200000D-02	26.672	.35104	5.0435	2511.0	9.3649
1.240000D-02	24.143	1.1173	14.577	2502.9	26.980
1.280000D-02	26.584	1.4752	20.983	2528.1	39.226
1.320000D-02	31.016	.92035	15.106	2555.9	28.552
1.360000D-02	30.867	.20397	3.3486	2543.0	6.2971
1.400000D-02	26.431	.38499	5.4840	2509.7	10.178
1.440000D-02	24.148	1.1567	15.090	2503.7	27.939
1.480000D-02	26.836	1.4668	21.043	2530.1	39.371
1.520000D-02	31.183	.87173	14.381	2556.6	27.189
1.560000D-02	30.673	.18574	3.0325	2541.2	5.6985
1.600000D-02	26.195	.42152	5.9538	2508.4	11.044
1.640000D-02	24.170	1.1951	15.600	2504.5	28.891
1.680000D-02	27.094	1.4555	21.067	2532.0	39.445
1.720000D-02	31.331	.82307	13.641	2557.0	25.793
1.760000D-02	30.466	.17125	2.7792	2539.2	5.2184
1.800000D-02	25.968	.46011	6.4457	2507.2	11.951

1.840000D-02	24.208	1.2318	16.099	2505.3	29.826
1.880000D-02	27.358	1.4412	21.046	2534.0	39.436
1.920000D-02	31.461	.77432	12.885	2557.2	24.366
1.960000D-02	30.247	.16020	2.5832	2537.2	4.8466
2.000000D-02	25.751	.50032	6.9535	2506.1	12.887
2.040000D-02	24.264	1.2665	16.584	2506.3	30.737
2.080000D-02	27.625	1.4237	20.978	2535.9	39.339
2.120000D-02	31.571	.72559	12.116	2557.3	22.913
2.160000D-02	30.016	.15259	2.4436	2535.2	4.5811

1 BASIC DC MOTOR SYSTEM

0 TL = 0

0 TIME	VEMF	IMP	TM	WMRPM	PWR
2.200000D-02	25.545	.54200	7.4754	2505.2	13.848
2.240000D-02	24.337	1.2991	17.055	2507.4	31.622
2.280000D-02	27.895	1.4032	20.862	2537.8	39.151
2.320000D-02	31.660	.67730	11.342	2557.3	21.448
2.360000D-02	29.776	.14855	2.3618	2533.2	4.4242
2.400000D-02	25.350	.58499	8.0096	2504.3	14.833
2.440000D-02	24.426	1.3294	17.509	2508.5	32.480
2.480000D-02	28.167	1.3797	20.697	2539.7	38.870
2.520000D-02	31.728	.62964	10.567	2557.0	19.982
2.560000D-02	29.529	.14809	2.3367	2531.2	4.3738
2.600000D-02	25.168	.62899	8.5526	2503.6	15.834
2.640000D-02	24.532	1.3573	17.944	2509.8	33.304
2.680000D-02	28.439	1.3532	20.481	2541.6	38.493
2.720000D-02	31.774	.58284	9.7974	2556.6	18.523
2.760000D-02	29.274	.15081	2.3610	2529.1	4.4156
2.800000D-02	24.998	.67380	9.1025	2502.9	16.848

1$$$ SIMULATION HALTED FOR FINISH CONDITION TIME 2.8000E-02

1 BASIC DC MOTOR SYSTEM

0 TL = 32.000

0 TIME	VEMF	IMP	TM	WMRPM	PWR
.0	.0	.0	.0	.0	.0
4.000000D-04	.92008	5.4719	92.088	73.949	5.0257
8.000000D-04	4.8203	7.8010	131.19	387.70	37.611
1.200000D-03	9.5372	8.1839	136.34	774.33	78.069
1.600000D-03	13.453	7.5780	121.81	1132.1	101.97
2.000000D-03	15.585	6.7204	100.37	1411.4	104.76
2.400000D-03	16.238	6.0510	82.595	1609.0	98.275
2.800000D-03	16.890	5.6101	73.185	1751.3	94.777
3.200000D-03	18.978	5.1302	70.438	1869.5	97.379
3.600000D-03	22.542	4.3328	66.834	1976.7	97.692
4.000000D-03	25.452	3.2843	55.057	2053.6	83.608
4.400000D-03	24.897	2.5359	41.135	2076.1	63.150
4.800000D-03	21.928	2.5434	36.589	2061.6	55.782
5.200000D-03	19.847	3.0453	39.937	2047.0	60.453
5.600000D-03	20.514	3.4185	46.219	2052.2	70.142
6.000000D-03	23.443	3.2341	49.358	2077.7	75.834

6.400C0D-C3	25.952	2.5913	43.359	2097.8	67.263
6.800C0D-C3	25.094	2.1171	34.462	2085.1	53.137
7.200C0D-C3	21.942	2.3101	33.404	2052.5	50.699
7.600C0D-C3	19.719	2.9357	38.575	2029.8	57.901
8.000C0D-C3	20.210	3.4027	45.774	2032.1	68.784
8.400C0D-C3	23.027	3.2955	49.876	2057.9	75.902
8.800C0D-C3	25.677	2.6899	44.862	2082.4	69.083
9.200C0D-C3	25.150	2.1843	35.796	2075.8	54.948
9.600C0D-C3	22.120	2.3178	33.882	2046.7	51.280
1.000C0D-C2	19.757	2.9183	38.515	2024.8	57.670
1.040C0D-C2	20.007	3.4112	45.552	2026.5	68.263
1.080C0D-C2	22.694	3.3537	50.160	2052.3	76.127
1.120C0D-C2	25.513	2.7691	45.949	2079.6	70.662
1.160C0D-C2	25.343	2.2181	36.605	2077.1	56.226
1.200C0D-C2	22.418	2.2841	33.797	2049.3	51.217
1.240C0D-C2	19.883	2.8606	37.972	2026.0	56.891
1.280C0D-C2	19.863	3.3858	44.913	2025.4	67.266
1.320C0D-C2	22.390	3.3865	50.041	2049.5	75.841
1.360C0D-C2	25.338	2.8338	46.734	2078.2	71.820
1.400C0D-C2	25.520	2.2478	37.321	2079.0	57.377
1.440C0D-C2	22.724	2.2490	33.682	2052.3	51.116
1.480C0D-C2	20.033	2.7991	37.407	2027.5	56.085
1.520C0D-C2	19.742	3.3538	44.239	2024.4	66.226
1.560C0D-C2	22.090	3.4132	49.830	2046.6	75.416
1.600C0D-C2	25.137	2.8977	47.450	2076.4	72.856
1.640C0D-C2	25.666	2.2834	38.102	2080.5	58.620
1.680C0D-C2	23.029	2.2195	33.640	2055.1	51.124
1.720C0D-C2	20.203	2.7381	36.874	2029.1	55.329
1.760C0D-C2	19.645	3.3176	43.565	2023.5	65.189
1.800C0D-C2	21.798	3.4348	49.550	2043.8	74.886
1.840C0D-C2	24.912	2.9608	48.098	2074.2	73.775
1.880C0D-C2	25.781	2.3246	38.940	2081.7	59.943
1.920C0D-C2	23.333	2.1956	33.670	2058.0	51.241
1.960C0D-C2	20.394	2.6777	36.371	2030.9	54.621
2.000C0D-C2	19.574	3.2771	42.890	2022.9	64.159
2.040C0D-C2	21.514	3.4509	49.201	2041.0	74.258
2.080C0D-C2	24.666	3.0223	48.667	2071.9	74.563
2.120C0D-C2	25.863	2.3708	39.823	2082.5	61.328
2.160C0D-C2	23.634	2.1775	33.776	2060.8	51.472

1 BASIC DC MOTOR SYSTEM

0 TL = 32.000

0

TIME	VEMF	IMP	TM	WMRPM	PWR
2.200C0D-C2	20.606	2.6183	35.899	2032.8	53.964
2.240C0D-C2	19.527	3.2327	42.216	2022.5	63.140
2.280C0D-C2	21.243	3.4613	48.790	2038.4	73.543
2.320C0D-C2	24.403	3.0814	49.150	2069.3	75.210
2.360C0D-C2	25.910	2.4213	40.736	2083.1	62.749
2.400C0D-C2	23.928	2.1653	33.959	2063.6	51.822

2.440000D-02	20.835	2.5605	35.460	2034.9	53.359
2.480000D-02	19.507	3.1847	41.548	2022.4	62.137
2.520000D-02	20.986	3.4660	48.323	2035.9	72.751
2.560000D-02	24.124	3.1378	49.544	2066.6	75.714
2.600000D-02	25.921	2.4759	41.666	2083.3	64.189
2.640000D-02	24.212	2.1594	34.223	2066.3	52.294
2.680000D-02	21.082	2.5047	35.060	2037.1	52.815
2.720000D-02	19.512	3.1335	40.889	2022.5	61.154
2.760000D-02	20.744	3.4650	47.808	2033.6	71.894
2.800000D-02	23.835	3.1910	49.846	2063.8	76.072

1$$$ SIMULATION HALTED FOR FINISH CONDITION TIME 2.8000E-02

1 BASIC DC MOTOR SYSTEM

0 TL = 64.000

0 TIME	VEMF	IMP	TM	WMRPM	PWR
.0	.0	.0	.0	.0	.0
4.000000D-04	-.54464	5.6231	94.624	-43.777	-3.0632
8.000000D-04	2.1216	8.2780	139.31	170.52	17.567
1.200000D-03	6.0096	9.0186	151.54	483.75	54.210
1.600000D-03	9.7738	8.6853	144.07	796.95	84.907
2.000000D-03	12.448	7.9217	126.51	1054.3	98.630
2.400000D-03	13.634	7.1866	107.31	1235.0	98.005
2.800000D-03	13.747	6.7085	92.606	1347.0	92.245
3.200000D-03	13.704	6.4703	84.800	1414.2	88.685
3.600000D-03	14.312	6.2975	83.313	1463.2	90.149
4.000000D-03	15.893	5.9976	85.187	1513.5	95.340
4.400000D-03	18.115	5.4763	85.541	1568.6	99.226
4.800000D-03	19.929	4.8192	80.465	1614.4	96.063
5.200000D-03	20.035	4.3046	71.510	1631.3	86.262
5.600000D-03	18.413	4.2082	64.839	1616.4	77.503
6.000000D-03	16.369	4.5202	63.099	1586.0	74.004
6.400000D-03	15.097	4.9919	65.441	1557.6	75.377
6.800000D-03	15.155	5.3381	70.833	1544.8	80.916
7.200000D-03	16.488	5.3725	77.039	1555.2	88.599
7.600000D-03	18.482	5.0649	79.930	1584.0	93.628
8.000000D-03	19.968	4.5704	76.591	1611.7	91.282
8.400000D-03	19.754	4.2030	69.439	1617.3	83.044
8.800000D-03	18.025	4.2214	64.400	1598.1	76.107
9.200000D-03	16.055	4.5924	63.589	1568.3	73.748
9.600000D-03	14.925	5.0728	66.364	1543.0	75.725
1.000000D-02	15.113	5.3979	71.915	1534.4	81.597
1.040000D-02	16.532	5.4016	77.980	1548.9	89.316
1.080000D-02	18.545	5.0688	80.438	1580.6	94.021
1.120000D-02	19.969	4.5659	76.632	1609.3	91.198
1.160000D-02	19.657	4.2109	69.336	1614.7	82.791
1.200000D-02	17.889	4.2485	64.432	1595.4	76.018
1.240000D-02	15.952	4.6290	63.774	1566.1	73.858
1.280000D-02	14.896	5.1034	66.690	1541.8	76.037
1.320000D-02	15.167	5.4105	72.329	1534.6	82.080

1.360000D-02	16.645	5.3916	78.285	1550.6	89.765
1.400000D-02	18.662	5.0413	80.394	1582.9	94.101
1.440000D-02	20.008	4.5369	76.231	1610.6	90.793
1.480000D-02	19.582	4.2006	68.924	1614.3	82.276
1.520000D-02	17.766	4.2630	64.270	1593.9	75.753
1.560000D-02	15.857	4.6571	63.848	1564.5	73.866
1.600000D-02	14.874	5.1284	66.959	1540.9	76.296
1.640000D-02	15.226	5.4191	72.709	1534.9	82.530
1.680000D-02	16.761	5.3788	78.560	1552.2	90.176
1.720000D-02	18.776	5.0125	80.318	1584.9	94.134
1.760000D-02	20.037	4.5084	75.816	1611.6	90.357
1.800000D-02	19.501	4.1922	68.527	1613.6	81.769
1.840000D-02	17.641	4.2793	64.130	1592.2	75.509
1.880000D-02	15.765	4.6861	63.942	1562.8	73.893
1.920000D-02	14.857	5.1531	67.243	1539.9	76.573
1.960000D-02	15.289	5.4268	73.096	1535.3	82.989
2.000000D-02	16.879	5.3651	78.823	1553.9	90.576
2.040000D-02	18.887	4.9833	80.220	1586.9	94.139
2.080000D-02	20.059	4.4808	75.391	1612.6	89.901
2.120000D-02	19.414	4.1855	68.144	1612.9	81.275
2.160000D-02	17.517	4.2969	64.006	1590.5	75.282

1 BASIC DC MOTOR SYSTEM
0 TL = 64.000

TIME	VEMF	IMP	TM	WMRPM	PWR
2.200000D-02	15.677	4.7153	64.048	1561.1	73.936
2.240000D-02	14.844	5.1770	67.537	1539.0	76.864
2.280000D-02	15.356	5.4333	73.482	1535.8	83.453
2.320000D-02	16.998	5.3501	79.069	1555.7	90.961
2.360000D-02	18.995	4.9536	80.098	1588.9	94.113
2.400000D-02	20.074	4.4539	74.956	1613.4	89.427
2.440000D-02	19.323	4.1803	67.775	1612.0	80.792
2.480000D-02	17.392	4.3156	63.898	1588.8	75.073
2.520000D-02	15.592	4.7446	64.167	1559.4	73.994
2.560000D-02	14.836	5.2002	67.841	1538.2	77.169
2.600000D-02	15.428	5.4384	73.868	1536.4	83.922
2.640000D-02	17.119	5.3340	79.298	1557.5	91.330
2.680000D-02	19.100	4.9235	79.951	1590.9	94.057
2.720000D-02	20.082	4.4279	74.516	1614.1	88.942
2.760000D-02	19.227	4.1768	67.419	1611.1	80.323
2.800000D-02	17.268	4.3354	63.805	1587.1	74.881

1$$$ SIMULATION HALTED FOR FINISH CONDITION TIME 2.8000E-02

1 BASIC DC MOTOR SYSTEM
0 TL = 56.000

TIME	VEMF	IMP	TM	WMRPM	PWR
.0	.0	.0	.0	.0	.0
4.000000D-04	-2.0090	5.7742	97.146	-161.51	-11.603
8.000000D-04	-.58469	8.7552	147.18	-47.044	-5.1202
1.200000D-03	2.3713	9.8626	165.88	190.70	23.393

1.600000D-03	5.6704	9.8406	165.65	455.89	55.846
2.000000D-03	8.5493	9.2665	154.63	692.95	79.238
2.400000D-03	10.488	8.5274	138.58	872.86	89.451
2.800000D-03	11.297	7.9037	122.35	987.08	89.310
3.200000D-03	11.207	7.5293	109.40	1043.3	84.397
3.600000D-03	10.694	7.4022	101.18	1058.2	79.175
4.000000D-03	10.211	7.4330	97.685	1050.9	75.913
4.400000D-03	10.040	7.5086	98.197	1038.4	75.403
4.800000D-03	10.302	7.5361	101.57	1033.9	77.656
5.200000D-03	11.012	7.4563	106.24	1045.3	82.126
5.600000D-03	12.086	7.2456	110.32	1073.7	87.589
6.000000D-03	13.300	6.9203	111.88	1112.7	92.058
6.400000D-03	14.253	6.5483	109.76	1150.2	93.353
6.800000D-03	14.490	6.2476	104.45	1172.4	90.550
7.200000D-03	13.882	6.1362	98.336	1171.6	85.198
7.600000D-03	12.743	6.2505	93.678	1150.1	79.669
8.000000D-03	11.525	6.5330	91.297	1115.5	75.310
8.400000D-03	10.574	6.8798	91.352	1077.1	72.762
8.800000D-03	10.071	7.1902	93.799	1044.2	72.431
9.200000D-03	10.075	7.3922	98.254	1025.2	74.489
9.600000D-03	10.573	7.4456	103.80	1025.8	78.740
1.000000D-02	11.501	7.3366	108.98	1047.3	84.400
1.040000D-02	12.693	7.0795	112.07	1084.5	89.877
1.080000D-02	13.816	6.7282	111.62	1126.4	92.979
1.120000D-02	14.408	6.3868	107.43	1158.5	92.040
1.160000D-02	14.154	6.1856	101.25	1169.6	87.572
1.200000D-02	13.205	6.2039	95.722	1157.6	81.941
1.240000D-02	11.987	6.4216	92.257	1128.6	76.994
1.280000D-02	10.906	6.7491	91.212	1091.5	73.622
1.320000D-02	10.212	7.0804	92.626	1055.8	72.320
1.360000D-02	10.007	7.3306	96.285	1030.5	73.376
1.400000D-02	10.307	7.4464	101.50	1022.8	76.767
1.440000D-02	11.071	7.4034	107.01	1036.0	81.983
1.480000D-02	12.184	7.2028	111.17	1067.8	87.779
1.520000D-02	13.388	6.8802	112.29	1109.5	92.130
1.560000D-02	14.258	6.5186	109.56	1147.4	92.960
1.600000D-02	14.364	6.2446	103.87	1168.0	89.718
1.640000D-02	13.659	6.1686	97.806	1165.2	84.272
1.680000D-02	12.496	6.3117	93.404	1142.2	78.891
1.720000D-02	11.318	6.6068	91.342	1107.3	74.793
1.760000D-02	10.444	6.9486	91.744	1069.9	72.584
1.800000D-02	10.031	7.2407	94.526	1039.3	72.645
1.840000D-02	10.123	7.4168	99.215	1023.6	75.097
1.880000D-02	10.703	7.4409	104.79	1028.0	79.660
1.920000D-02	11.693	7.3036	109.72	1052.8	85.422
1.960000D-02	12.902	7.0245	112.28	1091.8	90.650
2.000000D-02	13.970	6.6657	111.16	1133.1	93.136
2.040000D-02	14.428	6.3390	106.44	1162.2	91.479

	2.080C0D-02	14.032	6.1722	100.20	1169.2	86.627
	2.120C0D-02	13.004	6.2286	94.962	1153.7	81.014
	2.160C0D-02	11.784	6.4726	91.900	1122.6	76.289

1 BASIC DC MOTOR SYSTEM

0 TL = 96.000

0	TIME	VEMF	IMP	TM	WMRPM	PWR
	2.200C0D-02	10.756	6.8080	91.278	1085.1	73.241
	2.240C0D-02	10.141	7.1307	93.103	1050.6	72.329
	2.280C0D-02	10.024	7.3608	97.093	1027.8	73.797
	2.320C0D-02	10.407	7.4505	102.46	1023.6	77.554
	2.360C0D-02	11.242	7.3797	107.87	1040.3	82.981
	2.400C0D-02	12.394	7.1546	111.61	1074.6	88.689
	2.440C0D-02	13.574	6.8179	112.10	1116.6	92.567
	2.480C0D-02	14.337	6.4617	108.73	1152.4	92.664
	2.520C0D-02	14.295	6.2156	102.78	1169.2	88.867
	2.560C0D-02	13.479	6.1785	96.903	1162.5	83.200
	2.600C0D-02	12.285	6.3542	92.879	1136.8	78.077
	2.640C0D-02	11.141	6.6650	91.235	1100.8	74.268
	2.680C0D-02	10.338	7.0044	92.058	1063.9	72.426
	2.720C0D-02	10.011	7.2804	95.214	1035.3	72.897
	2.760C0D-02	10.189	7.4323	100.14	1022.8	75.144
	2.800C0D-02	10.847	7.4288	105.73	1030.9	80.598

0 TL = 0

0 TIME	THRST	SE1	SE2	SE3
.C	.0	1.0000	.0	1.0000
4.000C0D-04	.16264	1.0000	.0	1.0000
8.000C0D-C4	1.0943	1.0000	.0	1.0000
1.200C0D-C3	3.0994	1.0000	.C	1.0000
1.600C0D-C3	6.1526	1.0000	.0	1.0000
2.000C0D-C3	10.064	1.0000	.0	1.0000
2.400C0D-C3	14.626	1.0000	.0	1.0000
2.800C0D-C3	19.702	1.0000	.C	1.0000
3.200C0D-C3	25.217	1.0000	.0	1.0000
3.600C0D-C3	31.059	1.0000	.0	.0
4.000C0D-C3	37.045	1.0000	.0	.0
4.400C0D-C3	43.062	1.0000	.C	.0
4.800C0D-C3	49.125	1.0000	.C	.0
5.200C0D-C3	55.273	1.0000	.0	.0
5.600C0D-C3	61.471	1.0000	1.0000	.0
6.000C0D-C3	67.612	1.0000	1.C000	.0
6.400C0D-C3	73.677	1.0000	1.C000	.0
6.800C0D-C3	79.738	1.0000	1.C000	.0
7.200C0D-C3	85.860	1.0000	1.C000	.0
7.600C0D-C3	92.011	.0	1.C000	.0
8.000C0D-C3	98.098	.0	1.C000	.0
8.400C0D-C3	104.12	.0	1.C000	.0
8.800C0D-C3	110.15	.0	1.C000	.0
9.200C0D-C3	116.25	.0	1.C000	.0
9.600C0D-C3	122.38	.0	1.C000	1.0000
1.000C0D-C2	128.45	.0	1.C000	1.0000
1.040C0D-C2	134.46	.0	1.C000	1.0000
1.080C0D-C2	140.49	.0	1.C000	1.0000
1.120C0D-C2	146.59	.0	1.C000	1.0000
1.160C0D-02	152.72	.0	.0	1.0000
1.200C0D-C2	158.78	.0	.0	1.0000
1.240C0D-C2	164.79	.0	.0	1.0000
1.280C0D-C2	170.82	.0	.0	1.0000
1.320C0D-C2	176.93	.0	.0	1.0000
1.360C0D-C2	183.06	1.0000	.0	1.0000
1.400C0D-C2	189.12	1.0000	.0	1.0000
1.440C0D-C2	195.13	1.0000	.0	1.0000
1.480C0D-C2	201.16	1.0000	.0	1.0000
1.520C0D-C2	207.27	1.0000	.0	1.0000
1.560C0D-C2	213.40	1.0000	.0	.0
1.600C0D-02	219.45	1.0000	.0	.0
1.640C0D-C2	225.46	1.0000	.C	.0
1.680C0D-C2	231.50	1.0000	.0	.0
1.720C0D-C2	237.61	1.0000	.0	.0
1.760C0D-C2	243.74	1.0000	1.C000	.0
1.800C0D-C2	249.79	1.0000	1.C000	.0

0 TIME = 0
SW1
SW2
SW3

TIME
SW4
SW5
SW6

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